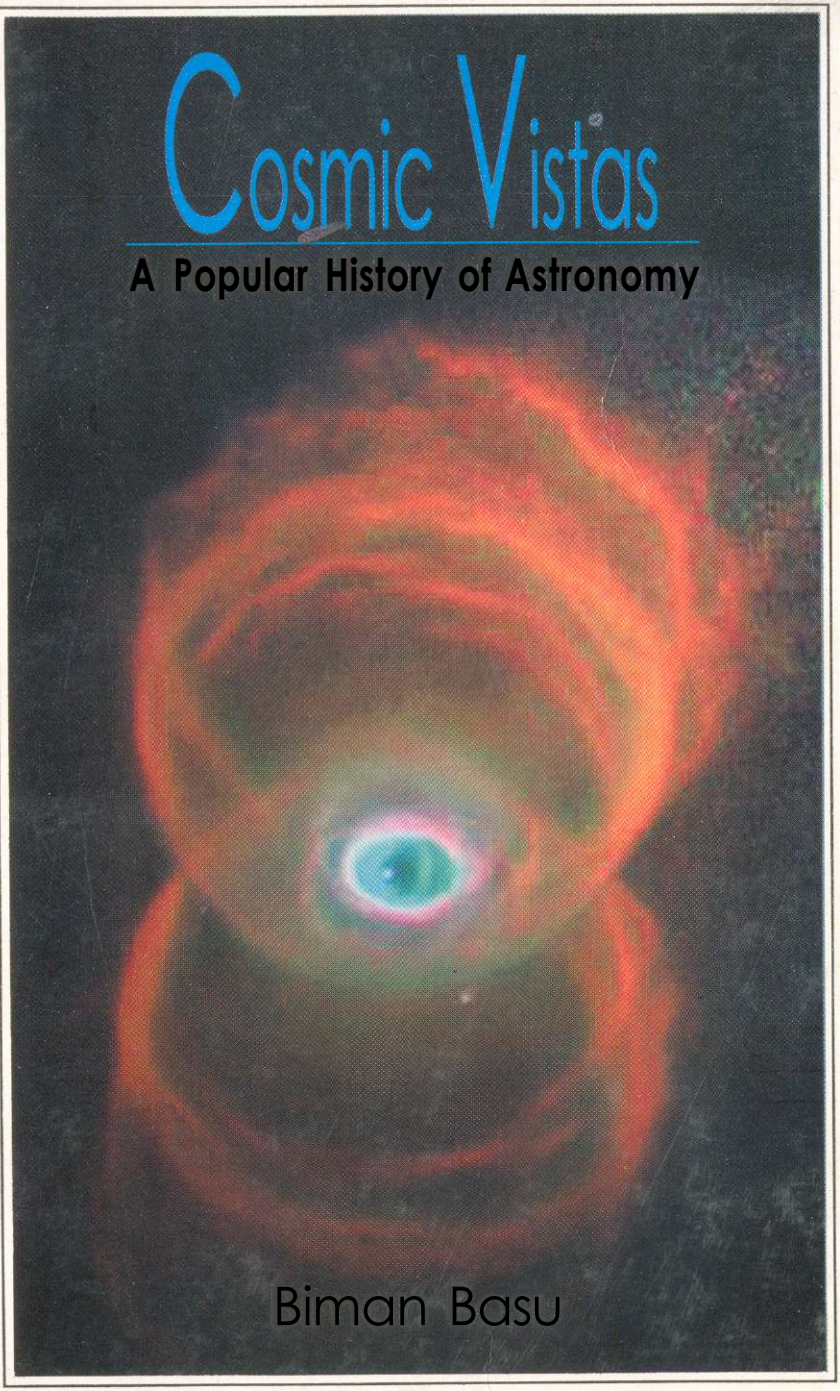
Cosmic Vistas

A Popular History of Astronomy



Biman Basu

Popular Science

COSMIC VISTAS

A Popular History of Astronomy

BIMAN BASU

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Acknowledgements

My interest in astronomy was kindled in my childhood when I watched with awe the star-filled night sky lying in a cot on the lawns of our house during the summer months. In subsequent years, I was inspired by the writings of eminent writers like Patrick Moore and Isaac Asimov. Although I never studied astronomy formally, my interest in the subject grew with age and I began enjoying sky watching more and more. I still remember the thrill of watching the famous Halley's comet in the early hours of a March day in 1986 and the glorious sight of the Hale-Bopp comet in 1997.

As I read more and more about the new developments taking place in observational astronomy, I was impressed by the enormous range of information available. But, sadly, reports of most of the breathtaking developments in astronomy remain hidden in research journals or in scattered articles published in popular astronomy journals. I decided to bring together all the exciting stories available on astronomical techniques and the remarkable discoveries made with the new techniques in a popular science book. The National Book Trust, India, helped me by agreeing to publish the book. I am grateful to them for the gesture.

One person who has constantly encouraged me in my astronomical forays including writing this book is the former Director of Positional Astronomy Centre, Kolkata, Prof. Amalendu Bandyopadhyay. I am deeply indebted to him for going through the original manuscript and making

valuable suggestions for improvement, which have helped me in bringing the text into its final form.

I am also indebted to all the authors whose books and writings have been of invaluable help in checking facts and figures for the book.

New Delhi BIMAN BASU

Preface

We all become familiar with the sky above right from our childhood days. We see the daily journey of the Sun across the sky the waxing and waning of the Moon and the star-filled night sky. But in my childhood days we hardly ever gave a thought to what these celestial objects were or why they behaved or moved the way we saw them in the sky We gradually learnt about them as we grew up. Today, however, things have changed. Children know a lot about the celestial objects thanks to the discoveries made by scientists over several centuries. The story of their discoveries has all the elements of a detective thriller. The exploration of space during the past four decades has further changed the scenario, revealing the solar system and the Earth's cosmic neighbourhood like never before.

To our distant ancestors, the Sun, Earth, Moon, planets and the stars made up the entire universe, with our Earth at the centre of it. Our ancestors believed that all the celestial bodies visible to the unaided eye—the Sun, Moon, five planets and the stars—move around the Earth in very complex paths. The ancient people did not even know what the stars and planets really were or how far they were from us.

There is, however, evidence that tells us that Vedic Indians, who probably lived more than 6,000 years ago, had considerable knowledge of astronomy. We find evidence of astronomical observations as early as 4,000 B.C. in the verses of the *Rig Veda.* But the oldest astronomical text in India is the *Vedanga Ji/otisha,* which is dated about 1,400 B.C.

Gradually, with advances in science and technology, as telescopes and other observation tools were invented to study the universe, the real nature and shape of the universe gradually unfolded. With the help of astronomical records of hundreds of years, the Polish astronomer Nicolaus Copernicus in the 16th century established the Sun at the centre of the planetary family we call the 'solar system'. Later work by Johannes Kepler and Isaac Newton explained the way the planets moved around the Sun, thus solving a long-standing riddle of planetary motions. But more than that, these developments shifted the position of the Earth from being the hub of the universe to that of an insignificant member of the solar family.

The invention of the telescope in early 17th century brought in a revolution of sorts. For the first time, a single technological development radically changed all our ideas about the universe. It revealed the real nature of the celestial bodies like the Moon, the planets, and the Milky Way—the galaxy of which the Sun and its planetary family is a part. As more powerful telescopes came, distant galaxies were discovered which extended the limits of our universe manifold. The vastness of the universe gradually started unfolding. Astronomers discovered that the stars that we see as tiny specks of light in the night sky are actually suns, many of them hundreds or thousands of times larger than our Sun. In fact, it turned out that our Sun is a very ordinary and medium-sized star the like of which there are billions and billions in the universe, making up billions of galaxies like our Milky Way galaxy.

As techniques of astronomical observation were further refined and newer tools were put to use, giant clouds of gas and dust were discovered in space where stars were being born. Astronomers also recorded the dying moments of giant stars that end up with flashes of brilliance so bright that sometimes they can be seen in broad daylight. Stars were found to be mortal, like us humans. They were born from giant clouds of gas and dust, lived till old age and

then died. Even our Sun will die eventually, but not in the near future. Astronomers say, it will continue to shine like it does now for at least 5,000 million years more.

Technological developments during the Second World War led to yet another breakthrough—the discovery of radio waves coming from space—that opened up a new dimension in our understanding of the universe. Galaxies and stars, and even our Sun, which appeared serene and shining steadily, turned out to be objects seething with extreme violence, spewing out highly energetic particles and powerful radiation. The universe as seen through the radio telescope appeared totally different from the visible universe we are familiar with.

Radio telescopes also brought forth new kinds of star-like objects, such as pulsars and quasars, the existence of which were never known before. Pulsars turned out to be fast-spinning dead stars that behaved like extremely accurate celestial clocks, sending out precisely-timed pulses of radio waves. Quasars on the other hand are extremely distant objects, which emit extremely powerful radio waves. The real nature of quasars and the source of their enormous energy still remain a mystery.

The study of radio waves from space also provided a proof of the way the universe was born, some 14 billion years ago. As early as in 1927, the Belgian priest and astronomer Abbe Georges Lemaitre had formulated the modern theory of the origin of the universe, which holds that the universe began in a cataclysmic explosion of a small, primeval 'super-atom', which is now widely accepted. The modern version was formulated by the Russian-born American physicist George Gamow and his associates in 1940. The British astronomer Fred Hoyle termed the cataclysmic event as 'big bang'. According to the big bang theory, initially the universe was extremely hot, only in the form of energy, which later cooled and condensed into various subatomic particles. These particles, in turn, came together to form atoms and molecules of hydrogen that filled the universe.

Cosmologists had predicted that if indeed there were a big bang, remnants of that gigantic explosion would be still present and could be detected as very short radio waves, known as microwaves, uniformly distributed in space. This all-pervading radiation was finally detected using radio telescopes in 1964. Subsequently, radiation in other wavelengths, such as infrared, ultraviolet, X-rays and gamma rays have also been detected from space, which have further changed our ideas about the universe. The new discoveries showed the universe around us to be an extremely violent place. If not in the vicinity of our solar system, violent activity goes on almost everywhere in the cosmos where massive stars explode in their death throes with the brilliance of thousand suns, or binaries collide spewing forth deadly gamma rays. There are also active regions where stars are born in stellar nurseries of dust and gas.

Our knowledge about the nature of the universe has undergone a sea change over the millennia since our early ancestors looked up at the sky. Ancient Greeks believed the universe to be an orderly system—a collection of a handful of celestial bodies—that worked with clockwork precision and called it 'cosmos'. Today we know that the cosmos is much more vast than the Greeks could ever have imagined. As this book will show, our present understanding of the cosmos has been made possible only because of the dedicated effort of the pioneers, and the scientific and technological innovations that we have witnessed in the past few hundred years. Without these marvels of science we may not have ever been able to fathom the almost limitless depths of our universe.

BIMAN BASU

1

IN THE BEGINNING

Human curiosity about the Sun, Moon and the stars is perhaps as old as the appearance of the modern human on this planet. As the early humans were evolving, their well-developed brain and an erect posture must have made them look up and wonder at the sky and the various phenomena going on there. The daily movement of the Sun across the sky from east to west, the changing phases of the Moon, and the sparkling star-speckled night skies must have appealed to him as it does to us even today. But unlike modern humans, the early humans did not have the means to study the celestial phenomena except with unaided eye. Their vision of the Earth, the sky and the universe was based solely on visual observations and their fertile imagination.

Yet, some of the ancient civilisations and prehistoric cultures had a surprisingly good understanding of the motions of the celestial bodies and of practical geometry. Around 4,000 B.C., Vedic Indians had considerable knowledge of astronomy, including the knowledge of the spherical shape of the Earth, phases of the Moon. Around 3,100 B.C. Stone-Age people in what is now United Kingdom had built one of the earliest astronomical observatories, in the shape of concentric circles of large standing stones. This group of standing stones at Stonehenge was probably used for marking the directions of sunrise, sunset, moonrise and moonset at different times of the year (*Plate I).*

About the same time as Stonehenge was being built, apart from India, much more advanced civilisations were

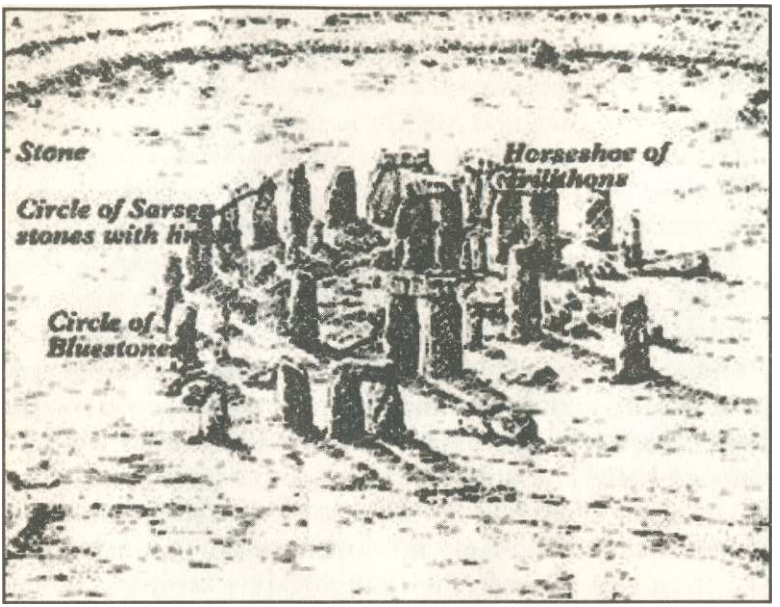

Fig. 1: An old sketch of Stonehenge showing the arrangement of rock slabs, which were used for astronomical observations.

flourishing in many other countries including China, Egypt and Babylon. Each had its own system of astronomy, inextricably mixed with astrology, mythology and religion. These ancient civilisations used their knowledge of the motions of the celestial bodies to make calendars and predict regular celestial events for organising various religious rituals. They also developed considerable skill in using the stars for finding directions and, consequently, for navigation at sea.

The Sun, Moon and Earth

Early ideas about the universe were primarily based on everyday observations and common sense. To us Earth-bound observers, the universe is all that we see around us—our Earth, the Sun, the Moon, the planets and the stars. We can hardly visualise things beyond what our eyes can see or our senses can feel. For example, although it is spinning around its axis and at the same time also going around the

Sun at a break-neck speed, we cannot feel the Earth move: So it is common sense to think that the Earth is standing still, as our ancestors believed. Similarly, early humans could only see the Sun, the Moon, five planets and a few thousand stars with the naked eye. So this was their universe. They could not imagine that there could be three more planets beyond Saturn or billions of galaxies outside our own galaxy that make up the real universe. They did not have the slightest idea about the vastness of the universe.

One of the first things in the sky that we all observe since our childhood days is the daily rising and setting of the Sun that constitutes the days and nights. The Sun is first visible over the eastern horizon at sunrise in the morning, heralding the day. Then it rises up in the sky till noon. After noon, it starts going down towards the west, finally disappearing below the western horizon at sunset, heralding the onset of night. The cycle repeats every day, although the length of the day changes from season to season. Our ancestors did not have any clue as to how this happened. Since the Earth appeared to be stationary, they thought the Sun must be moving across the sky. In some early civilisations, people believed that the Sun was carried across the sky on a chariot drawn by seven horses, which also brought it back to the eastern horizon at sunrise the next day Although we may find such ideas funny, they really did not appear so more than 4,000 years back, when the ideas about the universe were rudimentary and there was no way of finding out the truth.

More puzzling was the behaviour of the Moon. Unlike the Sun, neither did it rise and set at any fixed times during the day nor did its shape remain the same. It waxed and waned over a period of about a month, disappearing totally in between. Sometimes, the Full Moon appeared to darken and then regain its brightness again after some time. But more frightening was the disappearance of the Sun behind a dark shadow, which occurred only on some New Moon days. When it happened, the day suddenly turned

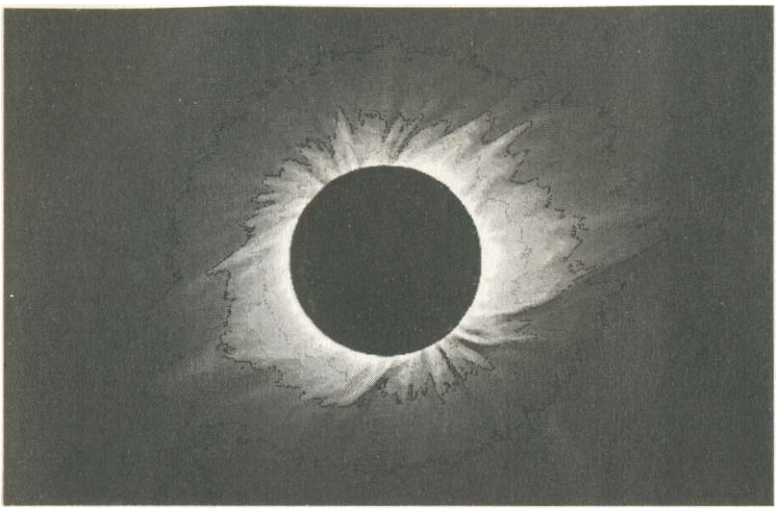

Fig. 2: The disappearance of the Sun during a total solar eclipse was a frightening experience for ancient people.

into night, birds returned to nests, animals behaved strangely and everything appeared eerie. Of course, the Sun always came out in its original glory in the end. But it was always a terrifying experience. We now know that these phenomena are nothing but lunar and solar eclipses, but our ancestors were totally at a loss to understand how such happenings could be possible and took them as ill forebodings.

Ancient humans also had no idea of the shape of the Earth, and understandably so. Even to us, when we stand in the middle of a vast field and if there are no hills around, the Earth looks flat and the sky appears like a giant upturned bowl. In an age when humans had not yet learnt to build ships and sail and had never ventured beyond the shores, they had no way of knowing that there existed lands beyond the seas. So, people in some civilisations believed that the Earth was like an enormous island, surrounded on all sides by seas and covered by the hemispherical dome of the sky, on which various celestial phenomena occurred.

According to one belief, the entire flat Earth was carried on the back of a giant turtle floating in the sea. The Egyptians believed the sky to be like a giant tent supported by the mountains.

Stars and Planets

If Galileo had not invented the telescope, our knowledge of the universe would never have progressed beyond the severely truncated view of the ancient people, who had no idea of the real nature or distances of the celestial bodies. The ancient sky-watchers were diligent observers, but they did not know what the stars were, what they were made of, how far they were, or how they were different from the planets. Of course, they were aware that the same stars appeared in the sky at the same time every year, but they did not know why. In contrast, some bright star-like objects, which today we know as planets, appeared to move across the sky in a random fashion, with no apparent regularity. Two of the planets could be seen only near the Sun before sunrise or after sunset. The ancient sky-watchers did not have any explanation for such apparently erratic behaviour of the planets.

Since the Earth was considered to be standing still, it was natural for the early sky-watchers to think that our Sun, Moon, the stars and planets all moved around a stationary Earth. No wonder, for thousands of years, the Earth was believed to be at the centre of the universe, with all the celestial bodies going around it from east to west.

Some of the earliest ideas were really fantastic. They suggested some kind of invisible 'canopies' over Earth, onto which the Sun, Moon and the stars were 'fixed'. As early as the 6th to 4th centuries B.C., Greek astronomers had realised that there must be more than one 'canopy' because, while the 'fixed' stars moved around the Earth without changing their relative positions, this was not true for the Sun, Moon and some of the star-like objects, which behaved differently. The star-like bodies, which moved in what appeared as

erratic paths, were aptly called 'planets', which in Greek means 'wanderers'. The Greeks believed that the Sun, the Moon and the five planets were each fixed to a separate invisible, spherical canopy of varying sizes.

The early sky-watchers were also aware of the cyclic change in the phase of the Moon and the fact that some of the bright stars were seen near the full Moon at certain times of the year. They made use of this knowledge about the regularity of some of the celestial phenomena as indicators of changing time and for preparing calendars. Some civilisations even used the positions of the stars to tell seasons, which greatly helped them in their hunting expeditions and sowing and harvesting of crops. The Egyptians, for example, after thousands of years of observations, knew that the early morning rising of the bright star Sirius was always followed by the flooding of the River Nile. It was important for Egypt's agricultural economy, and hence to the lives of the entire population of the Nile valley, to know in advance about the floods because the rushing waters brought in rich fertile soil as silt, which helped the Egyptian farmers grow bumper crops.

In India, Vedic priests used the knowledge of the motions of the Sun and Moon in the sky to plan sacrificial rites, which were an essential part of Vedic life. Knowledge of the stars was thus intimately connected with the daily life of ancient civilisations. Even today, festival dates in many countries including India are determined by the transit of the Sun from one constellation to another and the phases of the Moon.

Although our ancestors did not understand the celestial phenomena as we do today, their records of celestial events, painstakingly collected over centuries, have immensely helped later astronomers in unravelling the cosmic mysteries leading to our present understanding of the real nature of the universe. One of the earliest steps in this direction was the grouping of the brighter stars of the sky into various constellations and *nakshatras*, sometime around 4,000 B.C.

PATTERNS IN STARS

If we look at the clear sky on a dark, moonless night, the view can be bewildering.. The number of stars that we can see seems countless. Trying to make any sense of it appears almost impossible. So it may have been, till about 4,000 B.C. Then, two developments took place, which had far-reaching impact on the subsequent developments in our understanding of the universe. The first was the grouping of the brighter stars into various patterns called 'constellations' by the Vedic people, who probably lived on the coast of the Mediterranean in what is present-day Turkey (formerly known as Anatolia). Such grouping (of at least some constellations) may have helped them navigate at night, during their journey through unknown terrains. The second was the classification of star groups called *nakshatras* on the basis of the daily motion of the Moon in the sky, also by Vedic Indians.

The Constellations

After millennia of observation, the wandering people of the ancient world could make out patterns in the randomness of the star-filled sky. They could imagine familiar objects outlined by prominent stars, much like a child of today who makes up hidden figures by joining up the[1] dots in puzzle books. Ancient records in the form of prehistoric seals, vases and stone tablets mentioning the constellations date back only to around 2,000 B.C. But it is quite likely that the names of the 12 zodiacal constellations were of Vedic origin and

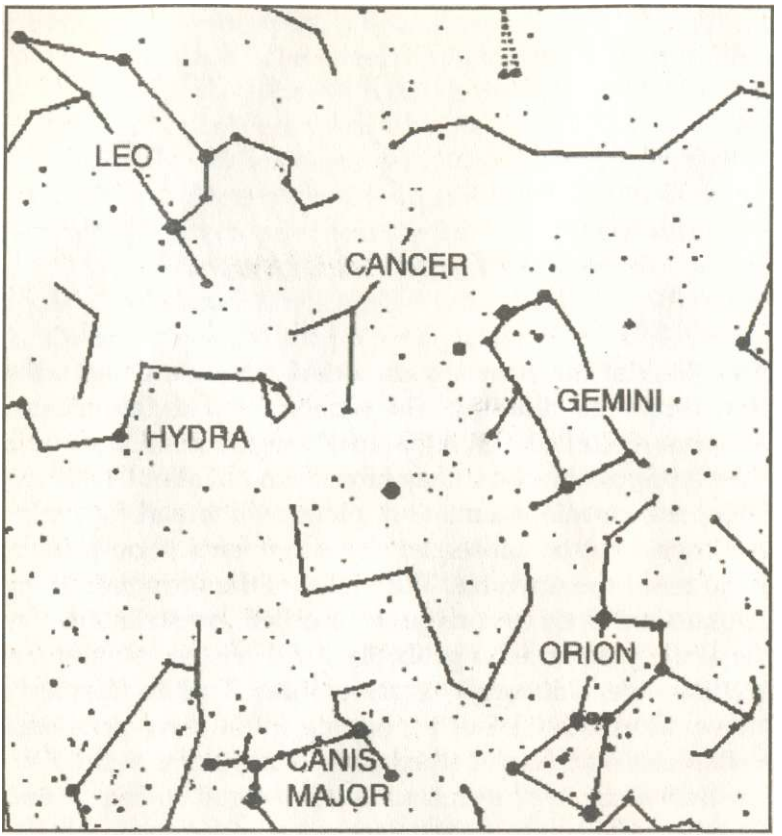

Fig. 3: Some of the popular constellations.

were taken up later by other civilisations, because the 12 signs of the Western zodiac coincide exactly with the 12 signs of the Indian zodiac mentioned in the *Rig Veda.* However, since the *Vedas* were passed on orally over thousands of years, there is no written text of the same. The oldest astronomical cuneiform texts, from the second half of the 2nd millennium B.C., record the Sumerian names of the constellations still known as the lion, the bull, and the scorpion — names that also find mention in Vedic hymns. Old engravings suggesting shapes of the scorpion, lion, hunter (Orion) and the big dipper (also found in the *Vedas)*

have also been discovered in China.

Of course, there can be many ways in which a group of stars can be joined to make a pattern. Thus, there is nothing sacrosanct about the constellations, except that they are creations of the human mind. No wonder, over the centuries, various civilisations have imagined their own patterns in the stars and given different names to their own constellations. But, anything meant for universal use has to be accepted by the international community, and that is what we have today.

The constellations we know today have been derived from a group of 48 known to the ancient Greeks (including those found in the *Rig Veda*) and listed by the 2nd century Greek astronomer Ptolemy in his astronomical work *Almagest.* These constellations were given names of animals or objects with which early civilisations were familiar. So we have Aries (the Ram), Taurus (the Bull), Leo (the Lion), Pisces (the Fishes), Libra (the Scale) and so on. Some of the constellations were named after Greek or Roman mythological characters, such as Andromeda, Cepheus, Hercules, Pegasus and so on. There were also interesting mythological stories associated with some of the constellations, which formed the lead characters in those stories. In some cases, different civilisations had different names for the same set of stars. For example, in the northern constellation of Ursa Major, the pattern of seven stars forming the tail of the mythical bear is known as the 'Big Dipper' in the West, but in India the seven stars represents seven sages and the asterism is known as *Saptarshi Mandal;* the constellation of Orion is known in India as *Kalpurusha,* and so on.

Interestingly, although some of the constellations do resemble the objects they are named after—Leo, Scorpius and Cygnus being prominent among them—most others rarely do. For them, one would have to have a really exceptional power of imagination to find any resemblance! Nevertheless, the grouping of the stars into recognisable patterns did help early sky-watchers to better understand

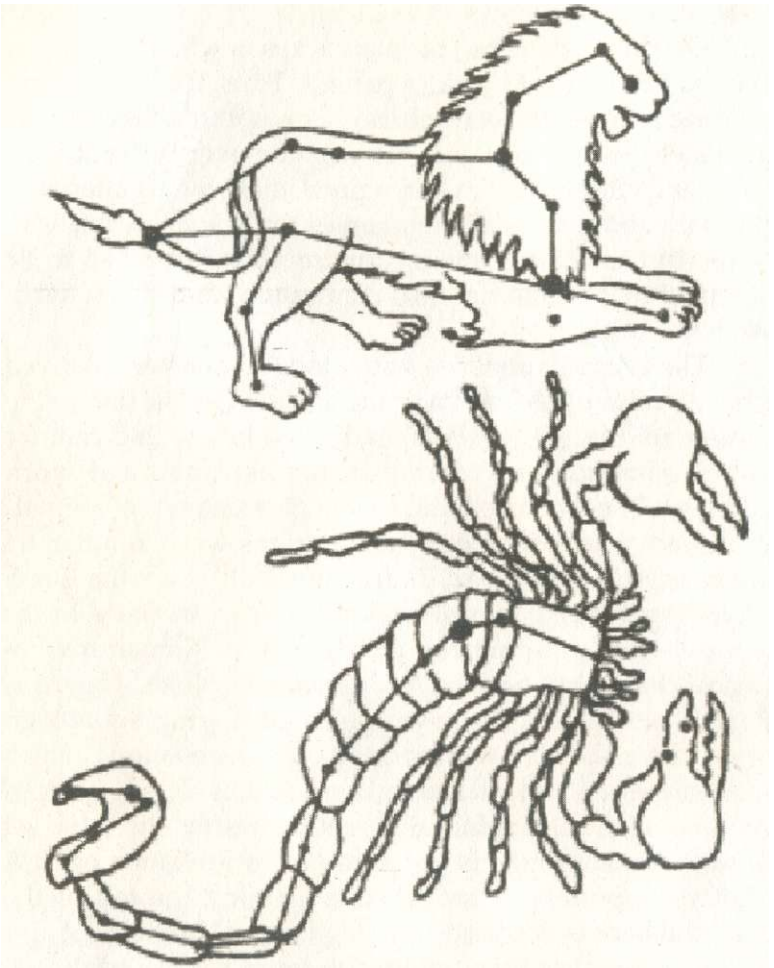

Fig. 4: Only a few of the constellations such as Leo and Scorpius resemble the objects they are named after.

their motion across the sky, because the constellations could be recognised more easily than the individual stars. The linking of the stars into groups and geometric patterns was also of great help in locating individual stars. More importantly, the constellations provided reliable guide-posts for the early seafarers who did not have anything else

other than the Sun, during the day and the stars at night to go by while in the high seas.

An interesting outcome of using the constellations as direction-finders at sea was the discovery of new constellations not visible from the northern hemisphere, something our ancestors may not ever have imagined. The new discoveries provided the earliest evidence that the Earth is shaped like a sphere. It was because of the spherical shape of the Earth that constellations visible from the southern hemisphere always lay below the southern horizon when seen from the north. But, once intrepid explorers sailed south of the equator, these southern constellations came into view and it is no wonder that as many as 12 constellations of the southern sky, not visible from the northern hemisphere, were discovered in the 16th century. Other constellations were subsequently added to the list. Today, a total of 88 constellations, into which the entire sky is divided, are recognised by the International Astronomical Union.

The Zodiac

As we have just seen, all the stars in the sky are grouped into 88 constellations. So, every star in the sky belongs to one constellation or another. Among the 88, there are 12 that straddle the sky along the apparent yearly path of the Sun, called the ecliptic. These 12 are known as the 'zodiacal constellations' and the band of the 12 zodiacal constellations is known as the 'zodiac'. The rest of the constellations are known as 'non-zodiacal constellations'. The 12 zodiacal constellations are: Aries (the Ram), Taurus (the Bull), Gemini (the Twins), Cancer (the Crab), Leo (the Lion), Virgo (the Virgin), Libra (the Scales), Scorpio (the Scorpion), Sagittarius (the Archer), Capricornus (the Sea-goat), Aquarius (the Water-bearer), and Pisces (the Fishes). A zodiacal sign denotes each of the zodiacal constellations. This division into 12 segments was probably made because there are 12 complete (actually about 12.4) lunar cycles or months m one year. As a result the Sun 'occupies' each segment, or

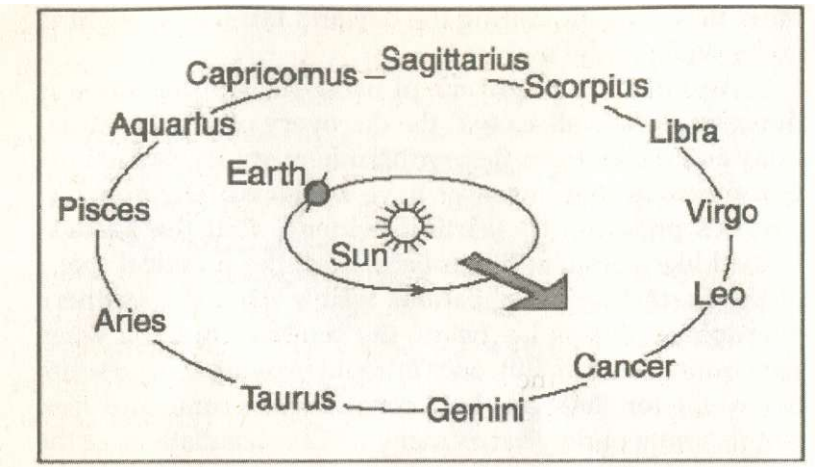

Fig. 5: The zodiac is an imaginary band of 12 constellations that marks the path of the Sun in the sky during the year.

'sign' for about one calendar month.

The importance of the zodiacal constellations lies in the fact that not only the Sun, but the Moon and the planets ?s well are seen to pass 'through' them during their apparent motion in the background of the 'fixed' stars. So the zodiacal constellations provide a convenient yardstick for measuring the daily, monthly and yearly movements of these celestial bodies across the sky Interestingly, although there are Indian names for all the 12 zodiacal constellations, except for a few bright constellations like Orion (*Kaalpurush),* Ursa Major (*Saptarshi Mandal),* and Corvus (*Hasta*), few other non-zodiacal constellations find mention in ancient Indian astronomical texts. As we shall see later, this may be because the Vedic Indians were basically interested in keeping track of the movements of the Sun and the Moon for preparing the calendar that fixed the dates of religious rites.

The *Nakshatras*

The zodiacal constellations were of special interest to Vedic astronomers in India, who were more interested in the

motion of the Moon in the sky. This interest could have been due to the much swifter motion of Earth's only satellite across the sky, which places it daily against a different backdrop of stars in the sky. No other celestial body moves as swiftly. More than 6,000 years ago, Vedic astronomers were aware that the Moon transits through every one of the constellations of the zodiac once in a little more than 27 days. To mark the position of the Moon every day, they divided the zodiac into 27 lunar 'mansions', each identified by a bright star or a group of stars, which they called the *naksliatra.* In later periods, the concept of the *nakshatras* played an important role in the development of a reliable calendar system, which remains valid even today.

The oldest system of Indian calendar, known from the *Vedanga Jyotisha* (composed as an aid to the *Vedas* around 1,400 B.C.) divides the solar year of approximately 354 days into 12 lunar months of 29.5 days, based on the daily movement of the Moon through the 27 *nakshatras.* To account for the resulting discrepancy between the solar and lunar years, a 'leap month' was added every few years, which made it a 'luni-solar' calendar.

The Wanderers

The grouping of the stars into easily recognisable patterns of constellations and *nakshatras* must have made it easier for early sky-watchers to detect and record the unusual and apparently erratic movements of some of brighter 'stars' that seemed to belong to no particular constellation, but weaved their way across the sky quite independently through the zodiacal belt. Their motions were complex; sometimes they moved forwards, sometimes backwards, and on certain occasions they appeared to stand still.

Of course, today we know that these bright star-like objects are planets, but the early sky watchers did not have any idea of what they really were nor did they know that, unlike the stars, they shone only by the light of the Sun. However, the irregular and what appeared to be erratic

motion of the planets may have made early humans to conjure up visions of some divine control of human destiny linked to the movement of the planets and this may have led to the beginnings of what we call 'astrology'. The different colours and speeds of their apparent motion in the sky against the background of stars may have also made early sky-watchers endow the visible planets with evil or goodness that form the mainstay of astrological predictions, although there is no scientific basis for such beliefs.

Telescopic observation and exploration by space probes during the 20th century, however, have changed all our early ideas about the stars and planets. They have revealed what the stars and planets are made of, how far they are, and why they move in the sky the way we see them to move. What we know about the planets today also tells us that there can be no scientific basis to suggest that the planets can decide or influence human destiny in any way. But the interesting point is that it was the study of the sky, especially of the star patterns and the planetary positions among them, for astrological purposes that later evolved into the modern science of astronomy, and the early sky-watchers had an important role to play in this development.

3

VEDIC CONCEPTS

Among the earliest practitioners of astronomy were the Vedic Indians who lived about 6,000 years ago. (According to some authors the earliest Vedic period goes back to a little beyond 10,000 B.C.) In the *Rig Veda* we find certain symbolic hymns and references from which we can learn a lot about the astronomical ideas of the Vedic Indians. In fact, the hymns in the *Rig Veda* contain a considerable amount of astronomy, including the knowledge of the spherical shape of the Earth, and phases of the Moon.

Whatever their knowledge of astronomy, it appears that the Vedic people studied the sky not so much for understanding celestial mechanics or cataloguing the stars, as for religious purposes—for deciding the auspicious dates and times for various rituals, which were an essential part of their daily life. The Vedic priests were not only keen observers but also possessed good knowledge of the course of the Sun in the sky, the path and phases of the Moon, the planets, occurrences of eclipses and the like. Whether their rituals had any practical utility we don't know; maybe they were an essential part of their social customs. But in the process of observing and compiling the vast astronomical data, the Vedic people have left behind a wealth of observational knowledge about the motions of the Sun, the Moon and the planets, in the form of Vedic *Samhitas* and *Brahmanas* and other literature.

Sun as God

As in many contemporary civilisations of the past, the Vedic people understood the importance of the Sun in sustaining life on Earth. They are also said to have believed that the stars are like the Sun but being far away appeared tiny. But they had no idea about the real nature of the Sun or how it produced so much energy; understandably so, because they had no means of finding it out for themselves. The *Rig Veda* describes the Sun as the sole light-giver of the universe (which, as we know today, is not quite true), as the cause of the seasons, and as the controller and lord of the world. Such an idea is not surprising, because the Sun was held in such high esteem and worshipped in many other early civilisations too, the most prominent being the Nile Valley civilisation in what is now Egypt, which flourished on the banks of the Nile around 3,000 B.C. Of course, we cannot deny the crucial role the Sun plays in sustaining life on Earth; but that is not because it has divine powers but because it is the source of enormous energy in the form of light and heat, the origin of which is nuclear fusion. And it is the light and heat of the Sun that sustains life on Earth.

The Vedic people also held the planets in high esteem. Unaware of their real nature, they described the five planets known at that time—Mercury (*Budha*), Venus (*Shukra),* Mars (*Mangala*), Jupiter (*Brihaspati*) and Saturn (*Shani*)—as gods, maybe because of their apparently strange motion in the sky. Although all this may appear ridiculous today, we have to remember that the ideas about the Sun, the Moon and the planets some 6,000 years ago were based on nothing more than simple naked-eye observation, and nothing more could be found out about the celestial bodies by this method.

The Calendar-makers

The Vedic people were a highly disciplined race. Their daily routine included various rituals, which they performed as prescribed by their religious texts. They also had some

sacrificial rituals, which had to be performed on specific days of the month or the year. Usually these coincided with the transit of the Sun and the Moon across certain star groups (constellations or *nakshatras)* in the sky or the occurrence of Full Moon or New Moon. The Vedic people needed a good knowledge of the measurement of time in order to correctly predict the times for the various rituals well in advance. Their meticulous studies of the motion of the Sun and the Moon across the various constellations and *nakshutrcis* in the sky enabled them to use the natural divisions of time caused by these motions for making reasonably accurate calendars.

With their intuitive minds the Vedic priests had developed a thought-pattern to explain the motion of the astronomical bodies. Because of its relatively good visibility and

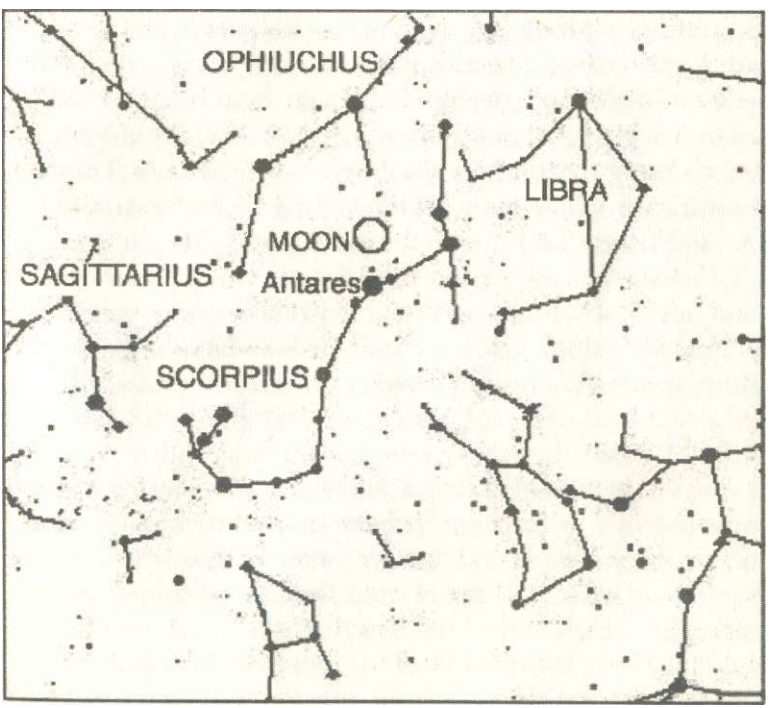

Fig. 6: The position of the Full Moon on 27 May 2002, near the star *Jyestha* (Antares), designating the Indian month of *Jaistha.*

fast movement against the background of stars in the night sky, the Moon became the obvious choice for determining the month. The Vedic people measured the lunar month from Full Moon to Full Moon (a system called *purnimanta*) or from New Moon to New Moon (called *amanta*), a period of a little more than 29 days, as it is still done. The lunar months, which we still follow, were named after those of the *nakshatras* near which the Full Moon was seen. For example, the first month of the Indian Saka calendar, Chaitra is named after the *nakshatra* called *Chitra* (Spica) in the constellation of Virgo; the month of Jyaistha is named after the *nakshatra* named *Jyestha* (Antares) in the constellation of Scorpio and so on.

As mentioned earlier, the Vedic calendar system was not based purely on the motion of the Moon, but was luni-solar; that is, it took into account motions of both the Moon and the Sun. Since 12 lunar months (of 29.5 days each) added up to only 354 days, three extra lunar months of 29.5 days, called 'intercalary' months, were added in an eight-year period to bring the average year-length to 365 days. This was a significant achievement of the Vedic Indians because without the periodic addition of the extra month, Hindu festivals, most of which are season-dependent, would have totally gone out of synchrony with the seasons over the years, as it is with the Hijira calendar followed in Islamic countries, which is purely a lunar calendar.

Units of Time

The Vedic people also had a fairly good knowledge of the variation of the day length between summer and winter and of the summer and winter solstices. However, unlike the present system of measuring the day from midnight to midnight, which makes the length of the day including the night the same, irrespective of the month or season, the Vedic people reckoned the day from sunrise to sunrise. This led to wide variation in the length of the day from season to season. The Vedic people broadly divided the day in two

ways. They divided the daytime into four equal parts, each called a *prahara.* The nighttime was similarly divided into four equal *praharas.* The *prahara* (equal to about three hours) was a very popular unit in Indian time measurement. An alternative system of division of time used by the Vedic people was the unit of the *muhurta.* The normal day was divided into 30 *mnhurtas* (one *muhurta* corresponding to 48 minutes)—15 *muhurtas* each of day and night. But in summer the longest day had a length of 18 *muhurtas* whereas the shortest day in winter lasted only 12 *muhurtas.* It is quite amazing how mere knowledge of the motions of the Sun and the Moon could be put to use to devise an accurate time-measuring system.

Although Vedic astronomy was largely observational, with very little effort to find theoretical explanations for the observed phenomena, it made significant contribution to our knowledge of the intricate relationship between the motions of the celestial bodies and the passage of time on our Earth. We still use variants of the Vedic system to fix dates of our festivals such as *Holi, Diwali, Raksha Bandhan, Makar Sankranti,* etc., which are decided by the position or phase of the Moon or the position of the Sun in the zodiac.

Large Numbers

An interesting aspect of the astronomical knowledge of the Vedic Indians was their knowledge of large numbers, which they used for calculating time. They had developed notions of the cycle of years, comprising round numbers of solar and lunar years taken together. They had even developed a system of larger cycles that took into account the revolutions of the planets, as they came back to the same position in the background of stars in the sky. The *Vedanga Jyotisha,* composed around 1,400 B.C., speaks of a five-year luni-solar cycle, called *yuga.* The beginning of the cycle was reckoned from the time both the Sun and the Moon are in the *nakshatra* named *Dhanistha,* which is identified with the present-day constellation of Delphinus. During one *yuga,* according to

the scheme, the Sun 'passed' through all the zodiacal constellations five times, and the Moon went through all the *nakshatras* 67 times. This relationship gave the length of a sidereal month as 27.31 days and that of a synodic month (the period between New Moon to New Moon or between Full Moon to Full Moon) as 29.52 days, which show the remarkable astronomical and computational knowledge of the Vedic Indians. The Hindu astronomers of the Siddhantic age expressed the periods of the Sun, the Moon and the planets by the number of their periods in a *mahayuga*—a period of 4,320,000 years—during which the planets, the Sun and the Moon return to their original position.

It is quite amazing how much wealth of knowledge about the celestial bodies could be amassed by the Vedic Indians merely on the basis of naked-eye observation and mental calculation. One reason may be their skill in mathematics, which enabled them to make highly accurate predictions about astronomical events, such as eclipses. But, as mentioned before, the Vedic people did not have any idea about the real nature of the astronomical bodies nor were they aware of the mechanism behind the apparent motions of the various celestial bodies in the sky, except, perhaps a vague idea about gravity. The earliest attempts to explain the various observed celestial phenomena began around 2nd century A.D., when theories of the 'solar system' were first put forward.

4

EARTH AT THE CENTRE

As we have seen, early observations of the motions of the Sun, Moon and the planets in the sky and the appearance of different constellations at different times of the year were documented by early sky-watchers mainly for time keeping and calendar making. In India, Vedic priests used them for predicting the dates and times for rituals and sacrifices. But hardly any thought was given to the question of how the Sun, Moon and the planets went about their celestial paths; what was the driving force behind them; what these celestial objects were made of; or how far they were from our Earth.

The first attempt to measure the Earth was probably made around 3rd century B.C. By measuring the different lengths of shadows cast at two places called Syene (now Aswan) and Alexandria (in present-day Egypt), 800 km to the northwest, at noon on the first day of summer, a Greek named Eratosthenes, the librarian of Alexandria, computed the circumference of the Earth to be 39,984 km, which is quite close to the modern value of 40,066 km. In 4th century B.C., Aristarchus of Samos observed that the Earth's shadow falling on the Moon during a lunar eclipse was always round. This he thought could be possible only if the Earth was shaped like a sphere and if the Sun was much larger than the Earth. He further conjectured that if it were really so, and if it was really the Earth's shadow falling on the Moon, then it would be absurd to imagine the much larger Sun going around a small Earth. The obvious

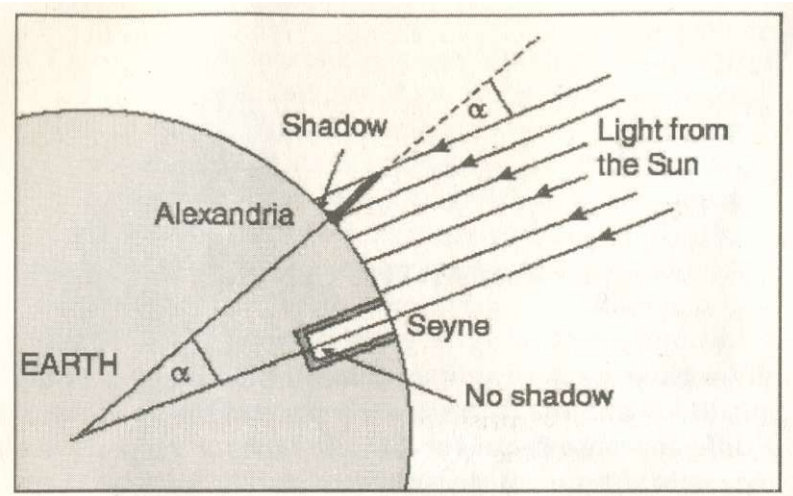

Fig. 7: The famous experiment of Eratosthenes, who showed by measuring the shadows cast at Syene and Alexandria that the Earth is shaped like a sphere.

conclusion would therefore be that the Earth and the planets go round the Sun and not the other way. This was a revolutionary idea at that time. But it did not go with the then prevalent belief that the Earth, the abode of mankind, was supreme and was at the centre of the universe, which was, in fact, accepted as a religious tenet. No one dared to suggest otherwise. So, no one gave much thought to Aristarchus's revolutionary theory that sought to displace Earth from that hallowed position. So, except for the conception that the Earth is a sphere, the work of these early Greeks did not do much to change the then prevailing ideas about the universe. The idea of the Earth being at the centre also did not conflict with the daily observation of the motion of the celestial bodies across the sky. So, at least for the time being, the Earth continued to reign supreme as being the centre of the universe!

Aristotle's Universe

One of the earliest accepted models of the universe is

credited to the Greek philosopher Aristotle, who lived in 4th century B.C. His was also essentially an Earth-centred or 'geocentric' universe. He argued that humans could not inhabit a moving and rotating Earth without violating commonsense perceptions. (If the Earth were moving we'd all fall over!) So, in the Aristotelian system, the Earth was fixed at the centre of the universe. The four 'elements'—earth, water, air and fire—were naturally disposed in concentric spheres, with earth at the centre, surrounded respectively by water, air and fire. Outside these were the invisible spheres on which the celestial bodies rotated. Such an idea was not surprising, because from land we can see water around and the sky above, from where the hot Sun gives us light and heat.

Ptolemy's System

One of the main problems with the geocentric, or Earth-centred, model of the universe was that it could not explain all the observed facts satisfactorily. For example, it could not explain why the pattern of stars, visible at night, changed with the seasons, or why the Moon waxed and waned over a period of a month. But one of the most troubling observations concerned the apparent motion of the planets against the starry background. Unlike the Moon, which steadily moved eastward against the background of stars each day, or the stars themselves, which moved westward a bit every night, the planets appeared to move without any set pattern. First they appeared to move westward against the background of the stars; then they appeared to stop in their paths and then move eastward (which astronomers call 'retrograde motion'). Again, they would appear to stop and finally move westward, as in the beginning. This cycle would be repeated after different intervals of time for the different planets. No simple model of celestial bodies revolving around the Earth could explain such an unusual motion. So, early astronomers took recourse to all sorts of complicated orbits, epicycles and other weird mechanisms to

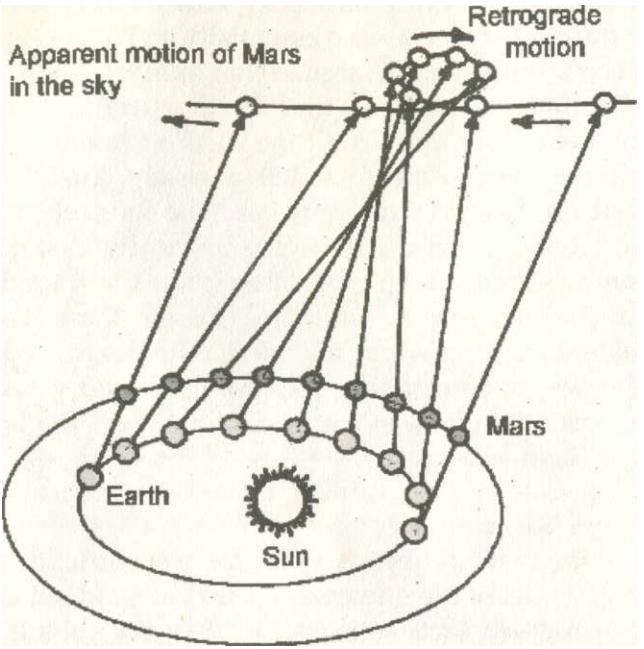

Fig. 8: The apparent backward motion of Mars in the sky is due to the Earth periodically overtaking it in orbit.

account for the apparently wayward motion of the planets.

To explain the motion of the planets, the 2nd century Greek astronomer Ptolemy (full name Claudius Ptolemaeus), who lived in Alexandria, proposed a complicated system of planetary motions in his famous work *Almagest.* Like others of his time, Ptolemy believed that the Earth was stationary at the centre of the universe and the Sun, Moon, the planets, and the stars revolved around it. To explain the various apparent motions of the celestial bodies in the sky, he proposed a complicated clockwork model of the universe. He imagined the planets to be revolving around small circles called 'epicycles' at a uniform rate, while the centres of the epicycles moved around in a larger circle whose centre was the Earth. In this model, the stars were thought to be fixed

to the inside of an invisible sphere, which rotated westwards.

Fig. 9: Ptolemy.

Ptolemy's epicyclic model could explain the observed motions of the planets reasonably well and was accepted by most astronomers for almost 15 centuries. But in course of time, with more accurate studies of planetary motions, astronomers found that they had to modify the Ptolemaic model by adding epicycles to the epicycles. Eventually the model became too cumbersome and complicated and many astronomers started finding it unconvincing, till the truth came out in the revolutionary theory of Nicolaus Copernicus in the 16th century.

Even after the Copernican theory, which placed the Sun at the centre, was published, the Danish astronomer Tycho Brahe put forward in 1583 another geocentric theory, which was a hybrid of the Ptolemaic theory and the Copernican theory. He retained Ptolemy's idea of a central Earth around which the Sun and Moon revolved, but he held that, as in the newer system of Copernicus, all other planets revolved around the Sun. In both the Ptolemaic and Tychonic systems, an outer invisible sphere containing the fixed stars was considered to revolve around the Earth.

A Spinning Earth

The great Indian astronomer Aryabhata, who lived around A.D. 500, also believed that the Earth was at the centre of the universe. Like Ptolemy he also considered the planets to move in epicycles to account for their retrograde motion in the sky. But in one respect he was ahead of Ptolemy. He believed that the Earth, which he said was spherical, like the *kadamba* flower, rotated on its axis to cause day and night.

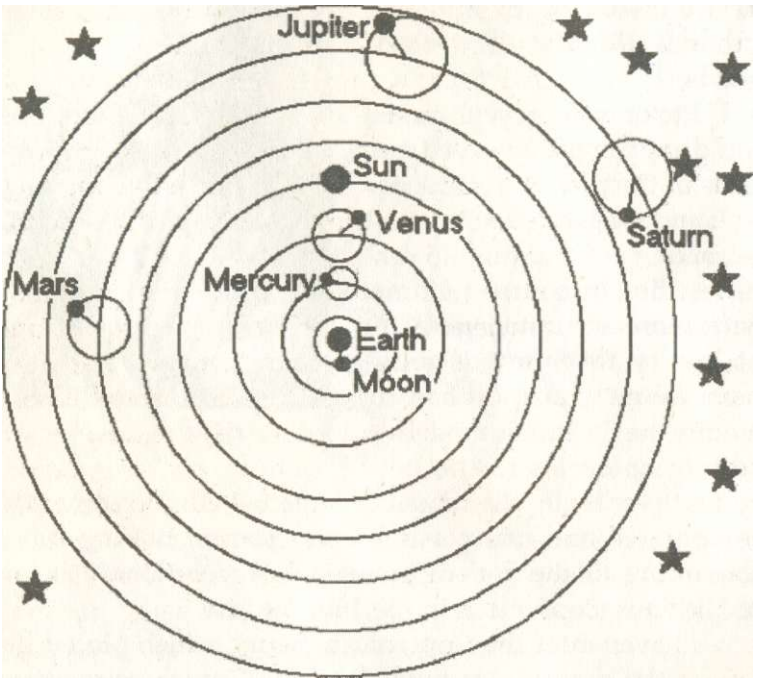

Fig. 10: The Ptolemaic system invoked complicated cycles and epicycles o explain the observed motion of the planets in an Earth-centred system.

To explain this he gave a beautiful analogy: "Just as trees and objects on the river bank appear to move in the opposite direction to a person going in a boat", he said, "the stars appear to move from east to west in the night sky because of the rotation of the Earth from west to east."

Early Indian astronomers had good knowledge of astronomical phenomena such as eclipses. Contrary to the Puranic idea of *Rahu* and *Ketu* devouring the Sun or the Moon to cause solar or lunar eclipse, Aryabhata held the view that eclipses were caused by the Moon obscuring the Sun and the large shadow of the Earth falling on the Moon respectively. Another Indian astronomer, Varahamihira, who lived around 6th century A.D., exploded the *Rahu-Ketu* myth by suggesting that the real cause of a lunar eclipse is the

entry of the Moon into the Earth's shadow and that a solar eclipse is caused when the Moon 'enters' the Sun. Bhaskara II, who lived in 12th century A.D., gave a very clear and lucid exposition on eclipses. He suggested that the orbit of the Moon being below that of the Sun, just as a cloud moving from behind covers the Sun so does the Moon; moving faster, it covers the Sun from behind, causing it to obscure the Sun.

All scientific theories develop through repeated refinements. As new deficiencies are encountered, changes are made to remove them. The theory of the universe had also to pass through many stages before it could account for all the observed celestial phenomena. Most of the theories of the universe proposed up to the 16th century considered the Earth to be at the centre, around which all celestial bodies revolved. There were deficiencies in the various models, which were sought to be removed by invoking complicated systems of cycles and epicycles. But no one dared to come out with a model that displaced the Earth from its hallowed position at the centre. It was left to the 15th century Polish astronomer Nicolaus Copernicus to make the breakthrough with his revolutionary Sun-centred theory of the universe.

5

PLACE OF THE SUN

As mentioned earlier, one of the earliest philosophers who gave a thought to the motion of the celestial bodies was Aristarchus of Greece, who was born in 320 B.C. in Samos Island, near present-day Turkey. After observing the Earth's shadow on the Moon during a lunar eclipse, he deduced that the Sun must be many times larger than the Earth. So, he reasoned, it would be absurd for so large a body as the Sun to revolve around so small a body as the Earth. And he came out with the suggestion that the Sun must be at the centre of the solar system and that the Earth and the other planets must be revolving around it. It was a revolutionary idea, but had no takers. The idea of the Earth, the abode of mankind, being at the centre of the universe was deeply ingrained in the minds of the people and was accepted as a religious dogma and no one dared to challenge it. It took 12 centuries for the idea of a Sun-centred universe to be revived. It was the genius of the 15th-century Polish astronomer Nicolaus Copernicus that finally freed the human mind from the shackles of religious dogma and Ptolemy's Earth-centred universe.

Copernicus's Universe

Copernicus was born in 1473 in Torun, Poland. He became interested in the study of astronomy when he joined the University of Krakow in 1491. In 1497, he was sent to the University of Bologna in Italy for further studies. It was at Bologna that he became acquainted with the astronomical

Fig. 11: Nicolaus Copernicus.

ideas of the day and made his first astronomical observations. He later joined the University of Padua to study law and medicine. After his studies in Krakow and Padua, Copernicus appears to have planned a systematic programme of astronomical studies. He did not make extensive observations, but did enough to enable him to recalculate the paths of the Sun, Moon and the planets around the Earth. He published 27 such observations made during the years 1497-1529.

In 1500, when Copernicus became a professor of astronomy at the University of Rome, he taught the traditional Ptolemaic astronomy, but he was never fully convinced of the idea of an Earth-centred universe. Once in 1502, so the story goes, while lecturing on the design of the universe he said, "The Earth is the centre of the universe; the Sun, Moon and the five planets revolve around our majestic Earth in a perfect circle. Beyond all these are the all-encompassing fixed stars. These are basic truths which were described by the great Claudius Ptolemy more than 1,500 years ago and which are evident to the senses."

A bright-eyed young man stood up to ask a question. "Learned professor", he spoke with a low voice, "did not the ancient Greek philosopher Pythagoras dispute this, saying that it is not the Earth but the Sun that is the centre of the universe?" Copernicus was about to respond, as he had many times before, asserting the Ptolemaic ideas. But, so the story goes, this time he hesitated to do that. He had so little faith in his usual answer that he dismissed the class

and abruptly left the room. After three years of teaching something that he did not believe in, Copernicus made up his mind to resign and return to his home in Poland, to devote himself to proving to his own satisfaction whether Ptolemy and the learned professors of his time were right or wrong.

Unanswered Questions

Copernicus's disbelief in Ptolemy's model probably arose out of its many inconsistencies and its inability to explain many of the observed facts satisfactorily. For instance, he was never quite happy with Ptolemy's cycles and epicycles, which made the model unnecessarily complicated. Further, it also could not explain why the brightness of the planets changed widely from time to time, or why the Moon showed phases, or why Mercury and Venus never rose much above the horizon. Copernicus also wondered if the Sun revolved around the Earth in the fixed orbit of a perfect circle, how could one account for the change of the seasons? His was a truly scientific mind.

After his return to his hometown in Poland in 1506, Copernicus practised as a physician and also served the church. In addition, like a true scientist he began his own observations of the sky in his spare time. Nights would find him in the tower of his mountain-top home, observing the stars and planets, making notations about their positions and reading all available manuscripts of the earlier astronomers. But Copernicus did not have the benefit of the facilities that today's astronomers enjoy. The telescope had not yet been invented and for much of the year in his native place, the local weather reduced the visibility of the sky. Naturally, progress was slow.

But nothing could dampen the spirit of this Polish astronomer. Using mathematical formulae and his own theory of the movement of the planets, Copernicus predicted the positions of Venus, Mars, Jupiter and Saturn. Then he anxiously scanned the sky as the years went by to see whether

his calculations were correct. To his great satisfaction, his predictions came out to be true; the planets were seen where he had predicted them to be. At last his doubts had been proved right. He now had evidence to show that the Ptolemaic theory of an Earth-centred universe was incorrect. He proposed to replace Ptolemy's theory with a model in which the planets, including the Earth, went round a centrally situated Sun, with the stars in the vast cosmos surrounding them all. This was an achievement of tremendous scientific significance.

The Sun at the Centre

What had actually prompted Copernicus to think of a Sun-centred model was the apparent looping motion of the planets in the sky during which, for some time, they appeared to move backward and forward in the background of the fixed stars. It took the genius of Copernicus to realise that these loops, which Ptolemy had sought to explain by epicyclic orbits, did not really occur, but were perceived as such due to the different orbital speeds of the Earth and the planets around the Sun. For example, as we know today, Mars being further away from the Sun takes about twice as long to go round the Sun as the Earth. As a result, the Earth periodically 'overtakes' Mars in its orbit when Mars appears to move 'backwards' in the sky. Similarly, since the orbits of Mercury and Venus were smaller than Earth's orbit, these two planets can never be seen far from the Sun, when seen from Earth. It is for this reason that none of these two planets can be seen in the sky for more than a few hours before sunrise in the dawn sky or after sunset in the evening sky. Thus Copernicus's Sun-centred model could in one stroke solve the mystery behind the apparent erratic motions of the planets and also do away with the need for the complicated epicyclic orbits to explain them. He showed by his calculations that the motions of all the planets follow precise mathematical laws as they went around the Sun in their respective orbits.

NICOLAI COPERNICI
ret, in quo terram cum orbe lunari tanquam epicyclo contineri diximus. Quinto loco Venus nono mense reducitur. Sextum denique locum Mercurius tenet, octuaginta dierum spacio circumcurrens. In medio vero omnium residet Sol. Quis enim in hoc
Sol.
pulcherrimo templo lampadem hanc in alio vel melior[i] loco poneret, quàm unde totum simul possit illuminare? Siquidem non inepte quidam lucernam mundi, alij mentem, alij rectorem vocant. Trimegistus visibilem Deum, Sophoclis Electra intuentem omnia. Ita profecto tanquam in solio regali Sol residens circumagentem gubernat Astrorum familiam. Tellus quoq; minime fraudatur lunari ministerio, sed ut Aristoteles de animalibus ait, maximam Luna cum terra cognationem habet. Concipit interea a Sole terra, & impregnatur annuo partu. Inuenimus igitur sub hac

Fig. 12: The Sun-centred system of Copernicus that revolutionised astronomy.

Although Copernicus had found the real clue to the motion of the planets by 1514, he was hesitant to make it public, afraid of being ridiculed and rejected by the Church, which had little regard for scientific ideas. (The world had to wait for almost 30 years before his work appeared in print; on the day he died in 1543.) His fear was not unfounded; dethroning Earth from its hallowed position as the centre of the universe could be construed as blasphemy. And without the Church accepting it, it would be impossible to get the western world accept the new theory. So, Copernicus decided not to publish his revolutionary theory, at least not for the time being.

Between 1510 and 1514, he prepared a brief, anonymous paper to summarise his new idea. It was titled *De hypothesibus motunum coelestium a se constitutis commentariolus* ('A Commentary on the Theories of the Motions of Heavenly Objects from their Arrangements'). In the paper, Copernicus put forward the suggestion that the apparent daily motion of the stars, the yearly motion of the Sun, and the apparently erratic behaviour of the planets resulted from the Earth's daily rotation on its axis and yearly revolution around the Sun, which is stationary at the centre of the planetary system. Therefore, the Earth, Copernicus proclaimed, is the centre of not the universe but only of the Moon's orbit.

Initially, for fear of ridicule, Copernicus privately circulated the paper among his friends. As the years passed, he further developed his arguments with diagrams and mathematical calculations. In 1533, he made a presentation of his ideas before the Pope in Rome, who is said to have given his approval. After his presentation before the Pope, Copernicus was formally requested by his friends in 1536 to publish his findings. But he continued to hesitate. It was left to his friends to go ahead and take up the responsibility of getting the work into print. A copy of Copernicus's revolutionary work, titled *De revolutionibus orbium coelestium* ('On the Revolutions of the Celestial Spheres') is said to have

been brought to the great astronomer at his bedside on the last day of his life, on 24 May 1543. He never actually read the printed book that changed for all times the worldview of the universe, by putting the Sun in its rightful place and giving a new perspective to our understanding of the universe. No wonder, the work of Copernicus has been described as "the greatest step ever taken in astronomy".

Religious Repercussions

The publication of Copernicus's theory had a deep impact on the development of astronomy and science in general, but not without some opposition. While Copernicus himself did not suffer any repercussions for attacking the established and Church-approved view of the universe, later scientists, the famous Italian Galileo among them, who went on to provide the proof of Copernicus's ideas, did suffer at the hands of those who did not want to give up the Earth-centred idea of the universe.

Another victim of the Roman Catholic Church's ire against the Copernican theory was the 16th-century Italian philosopher and astronomer Giordano Bruno, who rejected the Earth-centred Ptolemaic system and fearlessly went in support of Copernicus's Sun-centred model. Bruno had to pay for his beliefs by his life; he was arrested by the Inquisition and was burnt at the stake in 1600.

Fig. 13: The Italian philosopher and astronomer Giordano Bruno was burnt at the stake for supporting the Sun-centred system of Copernicus.

But, despite the opposition from the Church, the Copernican system appealed to a large number of independent-minded astronomers and mathematicians because

of its extreme simplicity and elegance. They not only accepted it but also expanded and advanced it. Apart from dethroning Earth from the centre of the universe, the Copernican heliocentric system also vastly expanded the size of the universe compared to what was believed earlier, as it placed the starry sphere far distant from Earth and the planets. But the Copernican model, too, had its deficiencies. It presumed the orbits of the planets to be circular, which as we know today, is not quite true. The Copernican model also did not provide any clue as to what made the planets go round the Sun.

Following the death of Copernicus in 1543, three notable astronomers—Tycho Brahe, Galileo Galilei and Johannes Kepler—carried his work forward. In a span of just eight decades, between 1560 and 1640, they made a great impact on the progress of astronomy. Then, in 1687, Isaac Newton came up with his universal laws of gravitation that provided an elegant explanation of what made the planets move.

4

PLANETARY PATHS

Copernicus's genius lay in his mathematical knowledge and power of rational thinking that helped him break away from centuries of orthodox beliefs. Through careful observation of the movement of planets in the sky and using his mathematical skill, he was at last able to come to a rational theory that was not only simple, but also could elegantly answer many of the questions about the motion of celestial bodies. No wonder, when Copernicus's revolutionary theory of a Sun-centred universe was published, it made a deep impact on the development of science and scientific thought, in general. But the Copernican theory was also not perfect; it assumed the orbits of planets around the Sun to be circular, which, as we know today, is not true. The planetary orbits are actually elliptical, or egg-shaped, which makes the distance of the planets from the Sun vary as they go about their respective paths. Also, the planets do not move with uniform speed around the Sun, as was believed by Copernicus; their speed varies as they come closer to and move away from the Sun while going round in their orbits. The credit for this startling revelation goes to the 16th-century German astronomer Johannes Kepler.

Tycho's **Legacy**

Although it was Kepler who enunciated the three laws of planetary motion, one astronomer who played a key role in his reaching that goal was a real-life Danish nobleman named Tycho Brahe. Tycho's interest in astronomy, surprisingly,

stemmed from his love for astrology. While he was studying law at the University of Copenhagen, several important natural events turned his interest from law to astronomy. The first was the total eclipse of the Sun predicted for 21 August 1560. Although Vedic Indian astronomers had predicted eclipses long before, for young Tycho, who had just turned 14, it was something magical. When the eclipse actually occurred, Tycho was so moved that he is said to have rushed out to get a copy of the Latin translation of Ptolemy's works. The professor of mathematics at the university helped him with the only printed astronomical book available, the *Almagest* of Ptolemy, the astronomer of antiquity who described the geocentric conception of the cosmos. Other teachers helped him to construct small globes, on which star positions could be plotted, and compasses and cross-staffs, with which he could estimate the angular separation of stars.

This was just the beginning; astronomy and astrology were to dominate the rest of Tycho's life. Once his interest in astronomy was kindled, Tycho was eager to learn more. He prevailed upon his uncle, with whom he lived, to send him to Leipzig University where he could study under the leading astronomers of his time. After he had assimilated all that they had to offer, Tycho started on a programme of self-instruction.

The second significant event in Tycho's life occurred in August 1563, when he made his first recorded observation—a conjunction, or close approach, of the planets Jupiter and Saturn. When he scrutinised the then existing almanacs and ephemerides, which contained predicted positions of the stars and planets, he found gross inaccuracies. The Copernican tables were off by several days in predicting this event. In his youthful enthusiasm, Tycho decided to take upon himself the task of making accurate observations of the sky to correct the existing tables. By the time he was 17, he had begun to chart his observations of the sky in a systematic manner. Between 1565 and 1572, he travelled

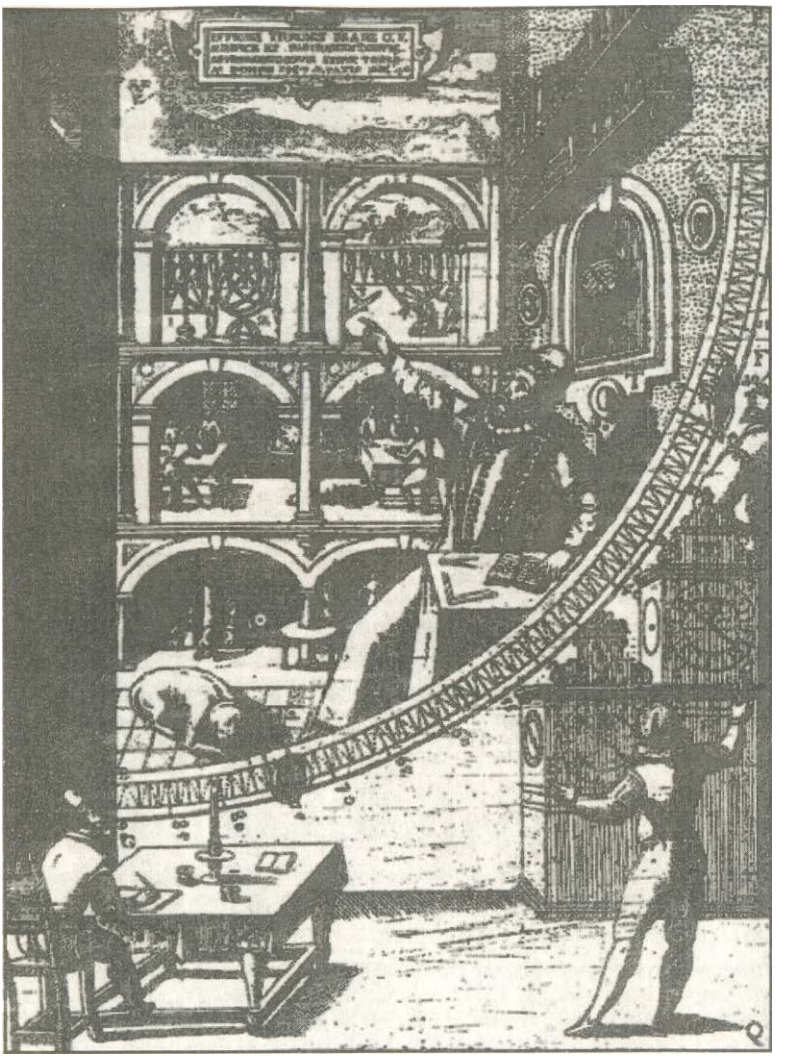

Fig. 14: Tycho Brahe's famous quadrant, which he used for measuring the coordinates of the stars and planets.

widely throughout Europe, studying and acquiring mathematical and astronomical instruments, including a huge quadrant, for making accurate astronomical observations. Tycho's scientific approach to astronomy was relatively new,

because the earlier studies of celestial bodies had been haphazard, mixed up with magic, superstition and mythology.

A New Star!

In 1571, Tycho built a small observatory at Scania, Denmark, where another important astronomical event of his life occurred. On 11 November 1572, Tycho suddenly discovered a 'new star' in the constellation of Cassiopeia where no star was supposed to be. The new star was brighter than the planet Venus and was visible during the day. Tycho's careful observations showed the new star to be much farther away than the Moon—probably at a distance where the other stars are. For the first time, a star had been seen to change in brightness so dramatically. This was a startling revelation, which went against the earlier held belief that the stars were permanent and unchanging.

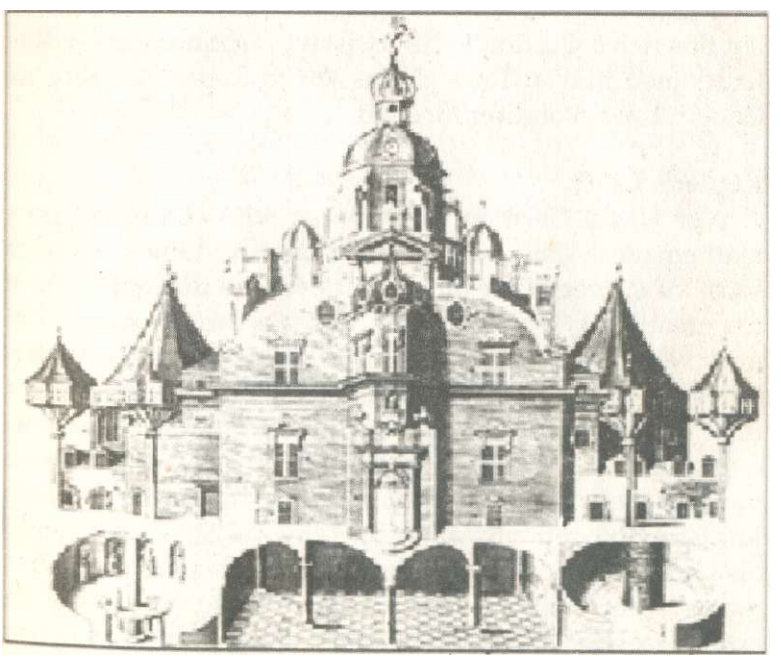

Fig. 15: The Uraniborg observatory of Tycho Brahe.

The discovery of the 'new star', which we know now as an exploding star called 'nova', encouraged Tycho to rededicate himself to astronomy He decided to establish a large observatory for regular observation of celestial events. He called his observatory 'Uraniborg'. It was from here that Tycho carried out most of his astronomical observations, fixing positions of the stars, which were to form the foundation of Kepler's historic work later. Tycho's observations—the most accurate possible before the invention of the telescope—included a comprehensive study of the planets and accurate positions of almost 800 stars. Tycho's measurements of the positions of the planets and stars had an unprecedented accuracy of about 2 arc minutes; that is, almost 1/30th of a degree.

By the time Tycho died in 1601, he had collected massive records, charts and note-books crammed with astronomical data that he had recorded himself painstakingly after careful measurements made over several decades. He left this rich collection to his assistant Johannes Kepler, who had joined him in 1600. It was left to Kepler to carry the Copernican revolution forward.

Kepler's Laws

Kepler was a German astronomer, who combined great mathematical skills with patience and an almost mystical sense of universal harmony. But even he did not come to his great discovery about planetary orbits at once; he almost went astray. Around 1590, he went to Graz, in Austria, to teach secondary school mathematics. It was around this time that a curious thought occurred to him. At that time, only six planets visible to the naked eye were known, namely, Mercury, Venus, Earth, Mars, Jupiter and Saturn. Kepler wondered why only six? Why not 20, or 100? Kepler also knew that there were five regular or 'platonic' solids, whose sides were regular polygons, as known to the ancient Greek mathematicians, since the time of Pythagoras. He thought that the two numbers were connected, and that

the five regular solids when nested one within another would perfectly specify the distances of the planets from the Sun. Kepler was immensely pleased with this 'discovery'.

Fig-16: Johannes Kepler,

But Kepler's joy was short lived. He soon found out that he was on the wrong track and that the platonic solids did not really fit in the scheme of things. No matter how hard he tried, the solids and the planetary orbits did not agree well. It was at this point that he got an offer from Tycho, the Imperial Mathematician in the court of the Emperor Rudolf II, to be his assistant. Before Tycho died in 1601, he bequeathed his observations to Kepler, paving the way for another revolution in astronomy.

After Tycho's death, Kepler became the new Imperial Mathematician and set about working out the planetary orbits with accuracies never known before. Apart from being a skilled mathematician, he was also a meticulous observer. He started working with the piles of data, which Tycho had bequeathed him.

It took five years for him to work out his first planetary orbit, that of Mars. His study of Mars's orbit brought out two deficiencies in the Copernican system. He found that Mars's orbit was not circular as presumed in the Copernican system; rather it was elliptical, with the Sun situated at one of the foci, that is, its distance from the Sun did not remain constant but varied as the planet went round the Sun. Kepler also discovered that Mars did not move with uniform velocity in its orbit, but sped up as it came near the Sun and slowed down as it moved away from the Sun.

Although Kepler made these path-breaking discoveries in 1605, he did not publish his results till the year 1609

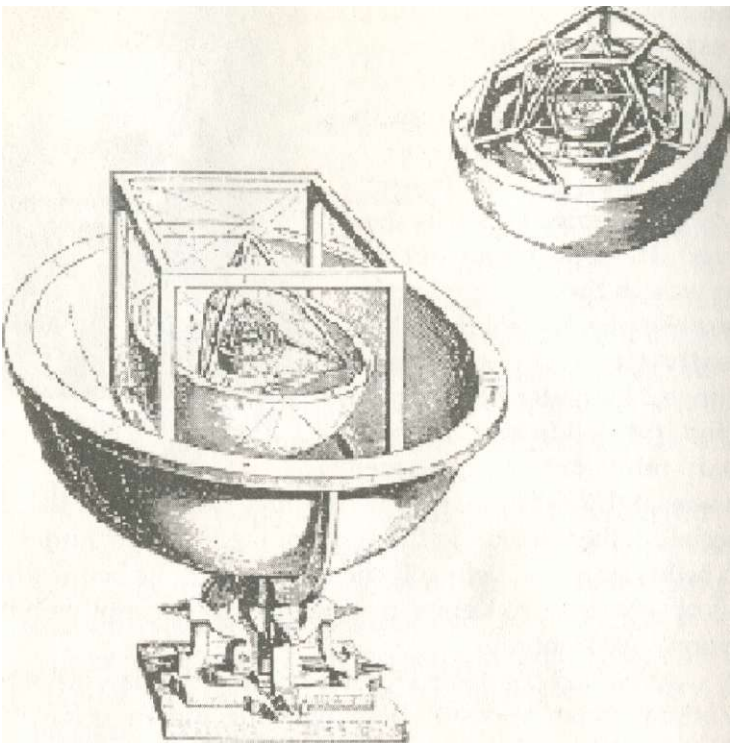

Fig. 17: Kepler mistakenly believed that the five regular platonic solids could explain the distances of the planets from the Sun.

in a book called *Astroncmia Nova* (or 'New Astronomy'). Almost a decade later, Kepler came up with another relationship in planetary motion; known as the 'harmonic law', it relates planetary distances with their orbital periods. He described it in a book called *Harmonice Mundi* ('The Harmonies of the World'). The three laws came to be collectively known as Kepler's laws of planetary motion, which can be stated as follows: (1) All planets move in elliptical orbits, having the Sun as one of the foci; (2) a radius vector joining any planet to the Sun sweeps out equal areas in equal lengths of time; and (3) the squares of the sidereal period of the planets (the times for them to complete one orbit) are

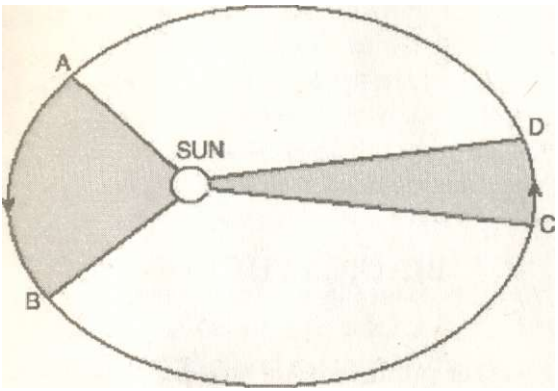

Fig. 18: According to Kepler's second law of planetary motion, it the takes a planet the same time to move from A to B as it takes to move from C to D, sweeping out equal areas as shown shaded. Thus a planet moves faster when nearer the Sun than when farther away.

directly proportional to the cubes of their mean distances from the Sun.

By the end of the first decade of the 17th century, astronomy had been transformed from a religious dogma into a perfect science. It was now possible to explain the observed astronomical facts with mathematical accuracy. But what made the Earth and the planets go round the Sun still remained a mystery.

In the meanwhile, another revolution in astronomy was in the offing with the invention of the telescope. In course of time, this optical tool would bring about a dramatic change in our understanding of the planets, the Moon and the Sun; indeed of the universe as a whole. It revealed a plethora of new facts unknown to astronomers before—the shape of the planets, rings of Saturn, moons of Jupiter, dark spots on the face of the Sun, and mountains and valleys on the Moon. The telescope also revealed the Milky Way to be a vast conglomerate of stars, invisible to the naked eye. The cosmos was turning out to be far different from the cosmos the early astronomers had imagined.

4

BEYOND THE EYE

By the time Kepler published his now-famous laws of planetary motion, a new invention was making its appearance in some European cities. It was this ingenious instrument, called the 'spyglass' that would launch astronomy on an entirely untrodden path.

The spyglass itself was nothing new, however. It had been around in Europe for quite some time. For several years lenses of various powers had been available to anyone entering a spectacle-maker's shop. Both convex and concave lenses were made routinely by spectacle-makers. Convex lenses—lenses that bulged outwards on both sides—were used for seeing enlarged images, mostly by the elderly, for leading. These were aptly called 'reading glasses'. But for those with nearsightedness, who had difficulty in seeing distant objects clearly, convex lenses were not the solution. They needed concave lenses—lenses that curved inward on both sides and were thinner in the middle than the edges. Objects looked smaller when seen through a concave lens. Around the turn of the 17th century, both kinds of lenses were available in any spectacle-maker's shop, but perhaps nobody had thought of putting two lenses of the right focal lengths at the two ends of a tube and looking through it. Finally someone did, in 1608. It must have come about accidentally. Someone must have playfully held a convex lens of low power (with a long focal length) in front of a concave lens of high power (with a short focal length), close to the eye, and found to his amazement that distant objects

appeared to be much nearer than they really were. When fitted at the two ends of a long tube, the device could be conveniently used to observe happenings at a distance without being seen. Perhaps for this reason it was called a 'spyglass'. It was the ancestor of the modern telescope.

Late that year, spyglasses began appearing everywhere, and all at once. On 2 October 1608, a Dutch spectacle-maker named Hans Lippershey applied for a patent on a "certain instrument for seeing far." His spyglass consisted of a tube made of lead at the far end of which was fixed a 'weak' convex lens and to the end nearer to the eye was fixed a 'strong' concave lens. Soon spyglasses became available almost throughout Europe. By 1609, one could buy a spyglass in shops of spectacle-makers in London, Paris, Milan or Venice.

Enter Galileo

The news of the spyglass also reached the University of Padua, Italy, where Galileo Galilei was a professor of mathematics. When Galileo, who had keen interest in astronomy, heard of the spyglass he was thrilled. He immediately got one and, as a true scientist, worked out the working principle. He used his knowledge of optics to figure out the mathematical relationship at the heart of the device's power to magnify; it turned out to be the ratio of the focal lengths of the objective lens and the eyepiece. Soon, he was able to design and build his own telescope of higher powers by grinding his own lenses.

During the late summer and autumn months of 1609, Galileo, along with an assistant, continued grinding, and polishing lenses and building longer tubes for his telescopes. By November 1609, he had completed one capable of magnifying 20 times, almost as good as today's amateur telescopes (*Plate II).* After Galileo, telescopes that used a convex lens as objective and a concave lens as the eyepiece came to be known as 'Galilean telescopes'. They are not only simple to build but also produce an erect image of the distant

Fig. 19: Galileo Galilei.

object and so can be used for terrestrial observations also. The only disadvantage of Galilean telescopes was their extremely narrow field of view; that is, they allow the viewing of only a very small part of the sky at a time. This shortcoming was removed by the use of convex lenses both as the objective and as the eyepiece.

But, building powerful telescopes was not Galileo's real contribution to astronomy. It was his use of the telescope for observing the celestial objects that really changed astronomy. On 30 November 1609, Galileo began his first telescopic study of the Moon from the garden behind his apartment in Padua. Unlike today's astronomers who work with photographic camera for recording their observations, Galileo used his pen and artist's brush to draw and paint what he saw. His observations of the Moon are meticulously recorded in his sketches, which bring out clearly some of the prominent surface features of our only satellite.

The *Starry Messenger*

In March 1610, barely three months after making his first formal observation of the night sky, Galileo published his findings under the title *Sidereus nuncius.* The real meaning of this Latin title was a 'message from the stars'; but for some unknown reason the English title became popular as the *Starry Messenger* or a 'messenger from the stars'. The book gave an illustrated account of Galileo's new astronomical observations. In the book, he first introduced the new instrument to his readers, "by means of which", he wrote, "visible objects, although far removed from the eye of the

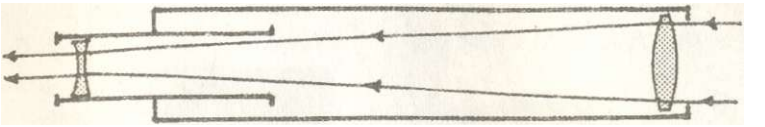

Fig. 20: The Galilean telescope uses a convex lens as objective and a concave lens as eyepiece.

observer, were distinctly perceived as though nearby."

About the Moon he wrote, "It is a most beautiful and delightful sight to behold the body of the Moon. It certainly does not possess a smooth and polished surface, but one that is rough and uneven and, just like the face of the Earth itself, is full of vast mountains, craters and valleys". He mentioned about the "large and ancient spots" on the Moon that are visible to the naked eye and about the spots "smaller in size and occurring with such frequency that they besprinkle the entire lunar surface". He also described the "uneven, rough, and very sinuous line" that divides the sunlit region of the Moon from the dark and the "very many bright points" that "appear within the dark part of the Moon", obviously referring to the sunlit peaks of the lunar mountains in shadow.

Galileo was surprised to find the profusion of stars when he turned his instrument towards the Pleiades cluster in the constellation of Taurus, and the Milky Way. In Pleiades, he found as many as 40 stars compared to only six visible to the naked eye. The Milky Way turned out to be a conglomeration of a multitude of stars. He wrote, "I have seen stars in myriads, which have never been seen before, and which surpass the old, previously known, stars in number more than ten times."

But the most momentous discovery reported by Galileo in his *Starry Messenger* was that of the four moons of Jupiter, which he had erroneously believed to be new planets. He wrote: "But that which will excite the greater

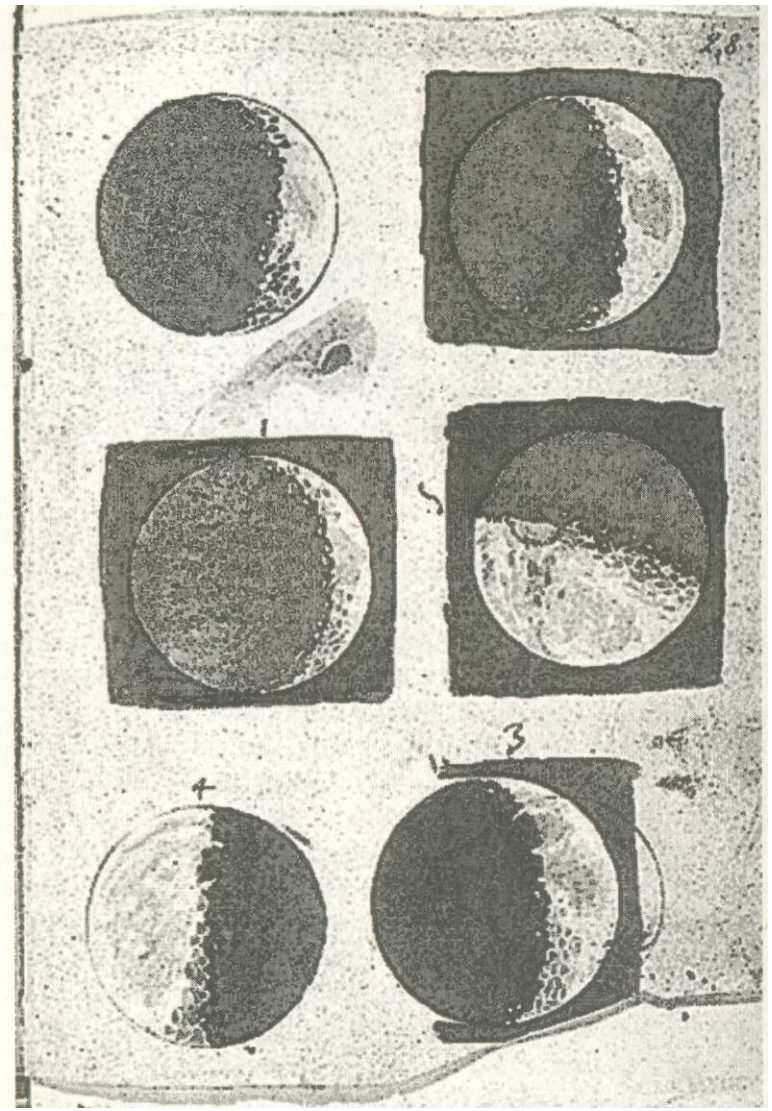

Fig. 21: Drawings of different phases of the Moon by Galiieo.

astonishment by far, which indeed especially moved me to call the attention of all astronomers and philosophers, is this, namely, that I have discovered four planets, neither known

nor observed by any one of the astronomers before my time." Of course, he soon realised that they were in fact tiny moons in orbit around Jupiter.

When observed over a period of several nights, the tiny moons of Jupiter appeared to change position in a manner that could be explained only by taking them to be satellites orbiting the mother planet, which appeared through the telescope as a disc. Galileo's analytical mind could immediately see a similarity between the moons of Jupiter and the planets orbiting the Sun in the solar system, as set out in the Copernican model.

The second convincing proof of a Sun-centred system came from the observation that Venus showed phases like our Moon. Galileo further observed that, as it changed from a full phase to a crescent phase, its size changed markedly, as would happen if it went farther away from Earth. At the crescent phase, Venus appeared almost six times bigger than at the full phase. If Venus really went round the Earth in a circular orbit, as contended in the Ptolemaic system, such a drastic change in its apparent size cannot be explained. Obviously, Venus was periodically moving away from Earth, when its bright face was visible, and moving nearer to Earth, when its dark side was turned towards us. Both these observations, namely, the changing phase and changing size of Venus could be explained if we presume that the planet goes round the Sun in an orbit which lies inside the orbit of Earth, as according to the Copernican model. His telescopic observations of the four moons of Jupiter and the changing phases of Venus convinced Galileo that the Copernican system was indeed the more plausible one than the old Ptolemaic model. We must remember here that both the observations about Jupiter and Venus that Galileo made and which provided irrefutable proof of the Copernican Sun-centred model would not have been possible without the invention of the telescope.

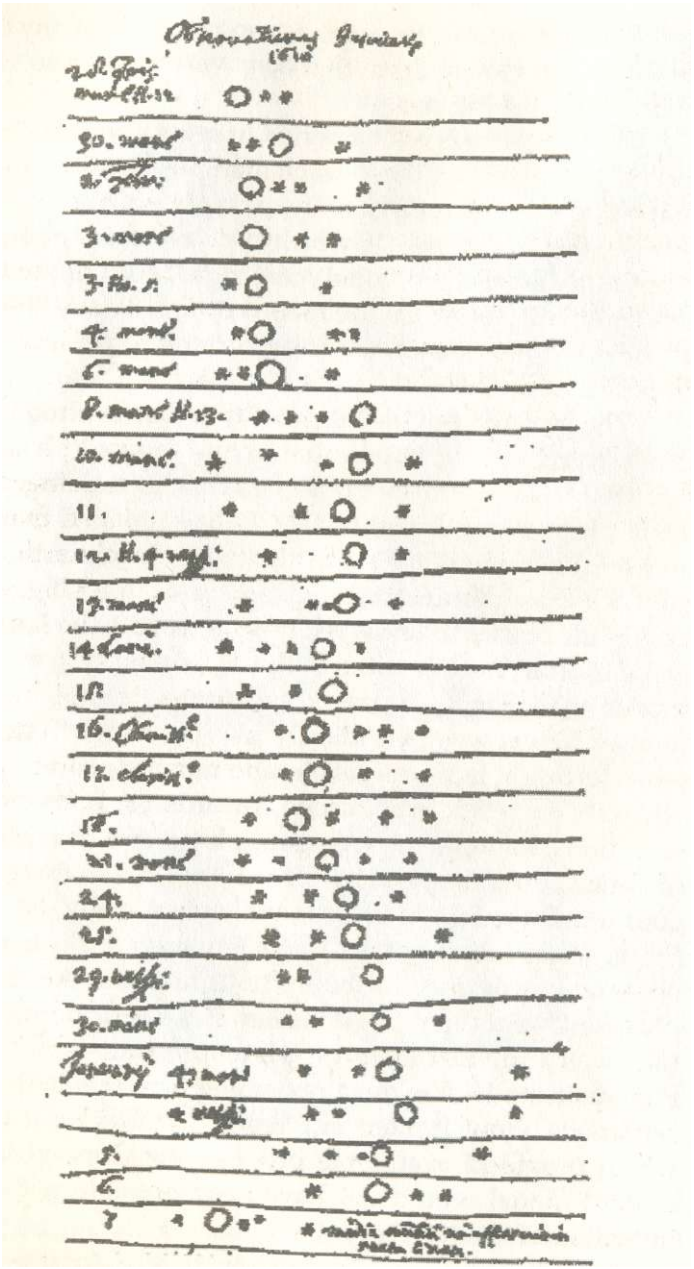

Fig. 22: Galileo's record of the movement of Jupiter's four large moons.

The Inquisition

Galileo's revolutionary astronomical findings and his endorsement of the Copernican theory, however, were not taken lightly by the religious authorities of the day Soon after his *Starry Messenger* was published, Galileo decided to return to Pisa from Padua to take up an appointment at the university. But it was a mistake, for in Pisa, instead of being acclaimed as indisputably establishing the truth of the Copernican theory, his book aroused hostility. The religious authorities in Pisa accused Galileo of trying to mislead the people by heresy. He tried to argue his case, but to no avail. He was warned to desist from spreading ideas contrary to those taught by the Roman Catholic Church, that the Earth was at the centre of the universe. It was a classic dilemma of a true scientist. The scientific tool was available, the observational records supported the correct theory, but society was not prepared to accept it.

Of course, as a true scientist, Galileo did not give up,

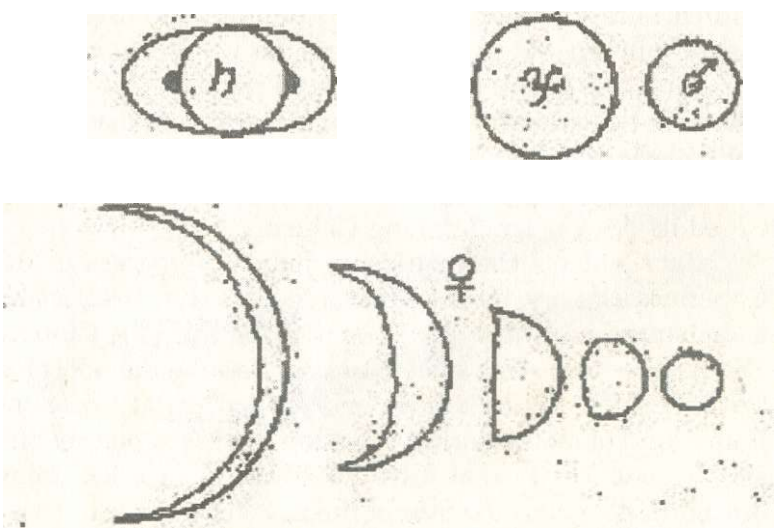

Fig. 23: Galileo's drawings of the phases of Venus (bottom row) along with Saturn's rings (upper left). The circles on the upper right denote Jupiter and Mars.

because he was convinced that the Church was wrong. He had full faith in the Copernican theory and tried to find innovative ways to tell the truth to the people. He wrote a book in the form of a discussion between three characters, which brought out clearly the fallacy of the Earth-centric ideas of Aristotle. In the book, titled *Dialogo sopra i due massimi sistemi del mondo, tolemaico e copernicano* (or 'Dialogue Concerning the Two Chief World Systems, Ptolemaic & Copernican'), published in 1632, he pulled to pieces Aristotle's conviction that celestial bodies never change and refuted physical arguments against Earth's mobility. In the *Dialogue's* witty conversation between Salviati (representing Galileo), Sagredo (the intelligent layman), and Simplicio (representing the Aristotelian), Galileo gathered together all the arguments, based on his own telescopic discoveries, in support of the Copernican theory and against the traditional Earth-centred cosmology.

But despite his best intentions, Galileo's literary ruse did not save him from the wrath of the Roman Catholic Church. A case was brought against him by the Inquisition and despite his old age and illness, he was summoned to Rome in 1633, where he was made to publicly declare that whatever he had written or said was heresy and that he did not believe that "the Sun is in the centre of the universe". (In 1992, the Roman Catholic Church formally acknowledged its error in condemning Galileo.)

But Galileo's trial could not halt the progress of the Copernican theory. By the time Galileo died in 1642, it had taken strong roots despite the opposition from the Church. The Sun-centred solar system almost became the accepted truth. Besides, Kepler's laws endowed planetary motions with a kind of mathematical precision unknown before. But, still, no one knew what force made the planets including our Earth go round the Sun in the manner they did. It was left to the English genius Isaac Newton to sort that out.

10

NEWTON'S GENIUS

On Christmas day, in the same year when Galileo died, a baby boy was born in the village of Woolsthorpe in Lincolnshire, England, who would grow up to become one of the greatest figures in the history of science. His name was Isaac Newton (*Plate III).* It was Newton's genius that finally solved the riddle of the motion of all celestial bodies and provided irrefutable evidence for the soundness of the Copernican model.

In 1665, at the age of 23, when Newton was an undergraduate student at Cambridge University, there was an outbreak of plague in England. The university had to be closed down for 18 months and Newton was forced to spend the time at his birthplace, in the village of Woolsthorpe with his mother. It was one of the most productive periods of his life. It was during this forced confinement that he invented the calculus—the branch of mathematics that deals with the study of continuously changing quantities—and developed the theory of gravitation. (The German mathematician Gottfried Leibniz also invented the calculus independently at the same time.) For 18 months, Newton concentrated on the problems that were to make him famous. It was during this time that he derived the rudiments of his law of universal gravitation after examining the mjtion of the Moon and the planets.

Newton's Calculus

Newton has been described by his biographers as being both

an experimental and mathematical genius, a combination that enabled him to establish both the Copernican system and a new mechanics. His method was simplicity itself: "From the phenomena of motions to investigate the forces of Nature, and then from these forces to demonstrate the other phenomena." Using the calculus, Newton worked out his now-famous three laws of motion and his theory of universal gravitation, which actually guided the motion of the planets.

Calculus is the branch of mathematics that helps mathematicians tackle continuously changing situations, such as a falling body, which moves faster and faster with time, as it approaches the ground. The story goes that Newton was inspired to devise the calculus after watching an apple falling from a tree. As an apple falls, it moves faster and faster; that is, it experiences acceleration as it falls. Newton expressed this change mathematically by supposing that at any stage of its downward motion the apple drops a small additional distance, denoted by As, during a brief additional time interval, denoted by At. The exact velocity v would then be the limit of As/At as At gets closer and closer to zero. The beauty and importance of the calculus is that, apart from enabling calculation of the velocity and acceleration of bodies in motion, it provides a systematic method for the exact calculation of areas, volumes, and other quantities that were beyond the methods of the early Greeks. The genius of Newton lay in his applying the calculus to determine and explain cosmic motions.

Newton's great achievement was to bring together all the significant discoveries made upto his time and to synthesise them into a single, basically simple, picture. On the basis of the observations and conclusions of Galileo, Tycho Brahe and Kepler (who had empirically figured out the elliptical nature of the orbits of the planets), Newton worked out his three simple laws of motion and the law of universal gravitation using his newly invented calculus. Without the calculus, Newton could not have worked out

his theory of gravitation since it involves the mathematics of bodies in motion, that is, of bodies continuously changing their position in space.

Force of Gravity

What Newton was really trying to do was to find out why the planets of our solar system keep moving in fixed orbits around the Sun, or what keeps the Moon going in orbit around the Earth. We can find a clue if we compare the motion of the planets around the Sun to the path described by a piece of stone tied to a string, which is swung round and round by a child. There is one important difference, however. In case of the whirling stone, the string held by the child exerts a constant pull, which keeps the stone from flying off and keeps it going round and round. But there is no such mechanical link between the Sun and the planets, or the Earth and the Moon. From simple analogy, Newton came to the simple conclusion that a planet keeps revolving around the Sun because the two attract each other, and same is the case with the Earth and the Moon. He further concluded that this attractive force works at a distance between bodies in space. Newton called this type of action at a distance 'gravitation'.

Using Kepler's third law of planetary motion, which states that "the squares of the orbital periods of the planets are proportional to the cubes of their average distances from the Sun", Newton mathematically deduced the nature of the gravitational force. He showed that the same force that pulls an apple down to the ground also keeps the Moon in its orbit. The famous anecdote of the falling apple comes from Newton himself and it epitomizes the genius of Newton. After all, things have been falling down since time immemorial and the fact that the Moon went round the Earth had been believed since all human history. But Newton was the first person ever to figure out that these two phenomena were due to the same force. This is the meaning of the word 'universal' as applied to Newtonian gravitation.

Using his mathematical skill, Newton was able to prove that this force of gravitational attraction declines inversely as the square of distance. This means that if two objects were moved twice as far away from each other, the gravitational force pulling them together would be only one-quarter as strong. If they were moved 10 times further away, the attraction due to gravity would become a hundred times smaller. It is due to this property of gravitation, as worked out by Newton, that a planet moves slowly when far from the Sun and faster when close to it. Kepler's second law of planetary motion also predicts the same, but Kepler did not know what caused the variation in speed. Newton's gravitation provided a mathematical answer.

In fact, all three of Kepler's laws of planetary motion can be derived from Newtonian principles. Kepler's laws were empirical, based upon nothing more than the recorded observations of Tycho Brahe. Newton provided a rigorous mathematical basis for them. But it took more than 20 years for Newton to publish his work, which he did at the behest of his friend, the famous British astronomer Edmund Halley (of Halley's comet fame).

The *Principia*

It was the summer of 1684. Newton was a professor of mathematics at Cambridge University. Halley came to see Newton for consultation regarding the forces that control planetary orbits. Specifically, Halley wanted to know what sort of orbit a planet would follow under the influence of a force that varies inversely with the square of the distance between the planet and the Sun. Many scientists had been working on this problem, but none of them had been able to come up with an answer. As mentioned earlier, Kepler had empirically worked out the planetary orbits to be elliptical on the basis of astronomical observations of the apparent motion of the planets in the night sky; he had no idea about the forces that made them behave so. But Newton had already worked it out using his calculus and came up immediately

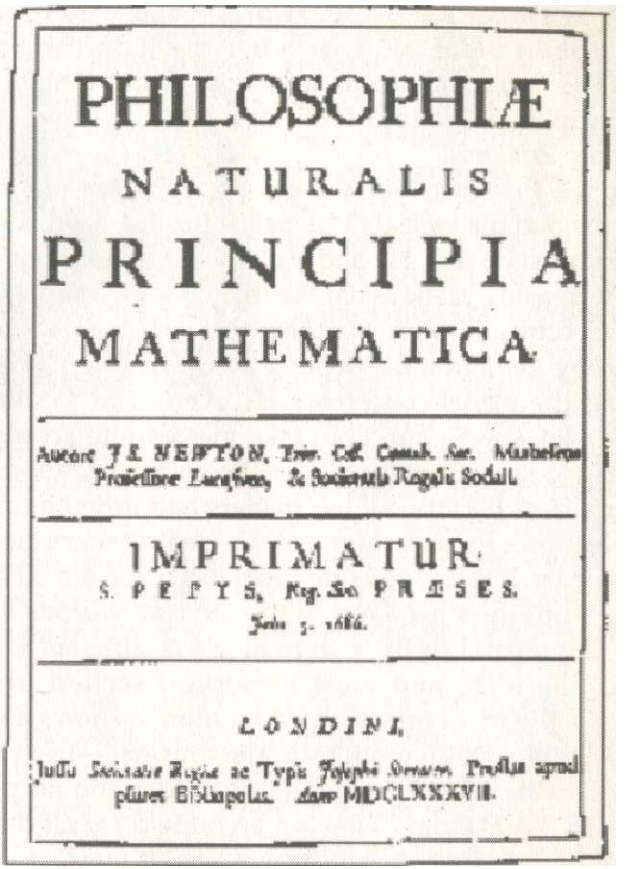
PHILOSOPHIÆ
NATURALIS
PRINCIPIA
MATHEMATICA
Auctore J.S. NEWTON, Trin. Coll. Cantab. Soc. Matheseos Professore Lucasiano, & Societatis Regalis Sodali.
IMPRIMATUR
S. PEPYS, Reg. Soc. PRÆSES.
Julii 5. 1686.
LONDINI,
Jussu Societatis Regiæ ac Typis Josephi Streater. Prostat apud plures Bibliopolas. Anno MDCLXXXVII.

Fig. 24: The cover of Newton's *Principia.*

with the answer. "It would be an ellipse, of course!" he replied. Halley was struck with joy and amazement; he asked Newton how he knew it. "Why," said Newton, "I have calculated it." When Halley asked him for his calculations without any further delay, however, Newton could not find them among his papers. Not to give up, Halley asked him to write it down again and send it to him.

Newton sat down to work on the problem anew. But he discovered that additional queries and new problems arose which he had to solve. Finally, his work was published

in 1687 at Halley's expense. With the passage of time his original short proof had grown into a volume, which was titled *Philosophiae naturalis principia mathematica* ("Mathematical Principles of Natural Philosophy"). It is better known simply as *Principia.*

In the *Principia,* Newton developed a detailed specification of what the force that keeps the planets in orbit around the Sun must be like. He had already shown early on that a force decreasing as the square of the distance could produce elliptical orbits. Now he was also able to show that the pull exerted by the Sun must depend on the masses of both the Sun and the planet concerned. He even went further than Kepler's laws, which did not take masses into account. He was able to show that there must be slight deviations from Kepler's laws because all the planets had different masses.

Newton's *Principia* is one of the greatest scientific books ever written. It is divided into three major sections. The first part sets out the three laws of motion and various laws of force. The second deals with motions in different kinds of fluids. The third and most important section presents Newton's theory of universal gravitation. It shows how this force accounts for all motions in the universe—from bodies on Earth to the celestial bodies like the Moon and the planets. In fact, in the *Principia,* Newton accounted for all the basic laws of motion that control the cosmos. It marked a major milestone in our understanding of the cosmos.

Cometary Paths

Newton's theory of gravitation not only explained the motion of the planets and their moons but also was able to throw light on the motion of one of the most mysterious objects then known to astronomy, namely, comets. Since time immemorial, comets had been objects of dread, for they seemed to appear and disappear without any obvious cause or reason. They were considered evil omens and were even believed to bring death and destruction. All the leading astronomers of the 17th century tried to account for comets,

Fig. 25: Edmund Halley, who was instrumental in the publication of the *Principia.*

but without much success. Now, using his law of universal gravitation, Newton found that he could predict what paths comets would follow through the solar system. He pointed out that the near circular (elliptic) orbits of the planets round the Sun were only one of the several possibilities. His calculations showed that objects could follow highly elongated orbits round the Sun that would take them beyond the farthest planet of the solar system. Newton conjectured that comets moved in this latter type of orbit, which made them appear in the sky after very long intervals; their paths were therefore, as predictable and understandable as any planetary orbit.

The triumph of Newton's ideas about comets came through the work of his friend Halley. While looking through records of past appearances of comets, Halley found that comets seen in 1531 and 1607, together with the one he had himself observed in 1682, seemed to be following a similar path around the Sun. He was bold enough to suggest that these were actually three appearances of a single comet, which orbited the Sun approximately every 76 years. So firm was his belief in Newton's calculation that he even went on to predict that the same comet would be seen again in 1758. Sadly, neither Newton nor Halley lived to see their predictions come true, but the comet did return in 1758 as predicted. Although he did not discover it, the comet was named 'Halley's comet' in honour of Halley. Since then the comet has returned thrice—in 1832, 1910 and 1986—every time vindicating NeWton.

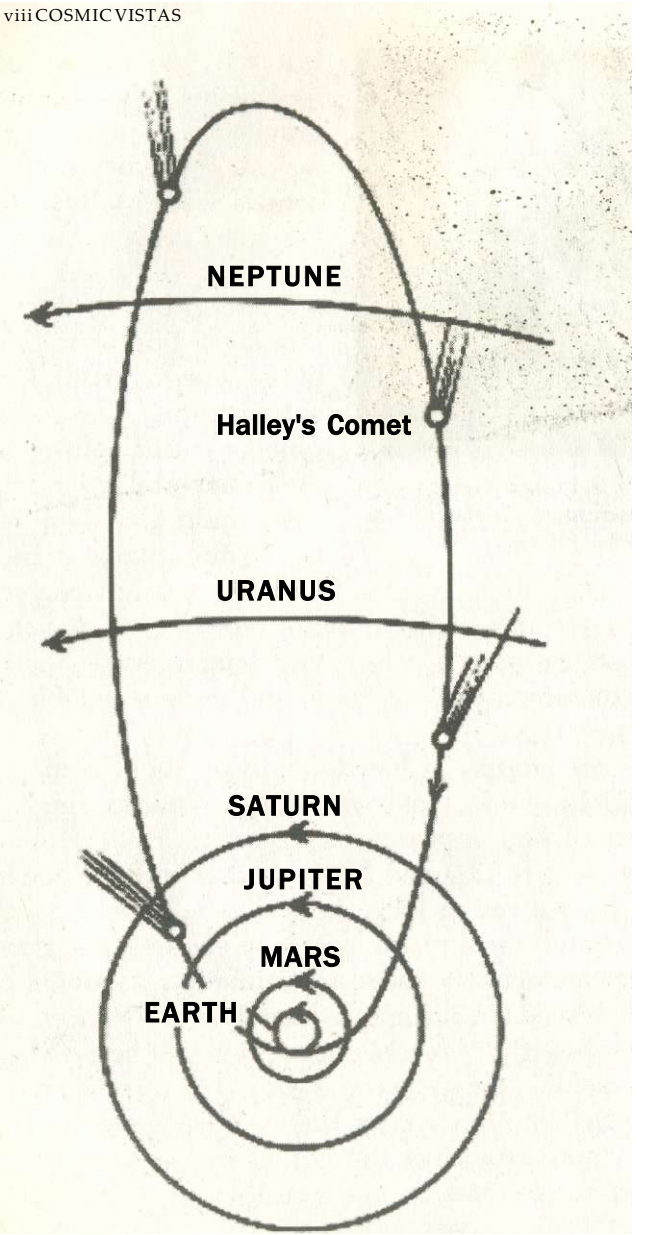

Fig. 26: The orbit of Halley's comet is highly elongated that takes it beyond the orbit of Neptune.

A New Planet!

Newton's theory of gravitation not only provided a scientific explanation for the motion of the planets and comets but also helped astronomers discover new planets in our solar system. The greatest triumph of Newton's law of gravitation came in 1846, when a new planet was discovered beyond Uranus in the solar system. The new planet, eighth of the solar family, was named Neptune.

The seventh planet of the solar system, Uranus, was discovered accidentally by William Herschel in 1781 during routine telescopic observation of star positions. But after calculating its orbit, astronomers discovered that the new planet was not quite following the calculated orbit. It was either lagging behind or moving ahead of its calculated position by a very small amount. The anomaly could be accounted for if one presumed the existence of an unknown planet in orbit outside the orbit of Uranus that was exerting a gravitational pull on Uranus, thereby disturbing the latter in its orbit.

It turned out that the gravitational pull of an outer planet was indeed the culprit. In 1841, a 22-year-old mathematics student of Cambridge University in England, named John Adams, decided to tackle the problem and worked at it in his spare time. By September 1845, he had an answer. Adams had worked out on the basis of Newton's law of

Fig. 27: Halley's comet photographed during its 1910 return.

gravitation where the unknown planet ought to be if it were to influence Uranus the way it did, but he was not lucky enough to discover the new planet. On the basis of Adams's calculations, the new planet was finally spotted in the sky on 26 September 1846 by a young French astronomer named Urbain Leverrier. The new planet was named Neptune. It was the first planet to be discovered purely on the basis of mathematical calculations of Newton's law of gravitation.

Thus Newton's gravitation finally brought the motion of the planets and other bodies of the solar system within the ambit of rigorous physical laws. There was now a firm scientific basis to explain not only how the planets moved in orbit but also why they moved the way they did. The revolution that Galileo had initiated at the beginning of the 17th century was triumphantly completed by Newton at the century's end. Astronomy would never be the same again.

Newton's theory of universal gravitation remained unchallenged for more than 200 years. Then, experiments conducted in the late 19th century and early 20th century brought to light the inadequacies in Newton's theories. In 1915, the work of a patents examiner in Berne, Switzerland offered physicists a new way of looking at gravity. It overcame the inadequacies of Newton's theory and added a new dimension to our understanding of the cosmos.

9

EINSTEIN'S UNIVERSE

Despite its many successes, Newton's theory of gravitation did not remain unchallenged. The challenge came in the form of an anomaly in the orbit of Mercury, the planet closest to the Sun. Years of observation had shown that Mercury's point of nearest approach to the Sun, or perihelion, changed from one orbit to the next. It moved forward a bit in each orbit. The anomaly could not be explained by Newton's law. If Newton's law were correct, every planet should follow exactly the same path forever, except for minor irregularities caused by the gravitational influence of other planets in the neighbourhood, as in the case of Uranus. But the change in Mercury's orbit was regular and could not be explained on the basis of the

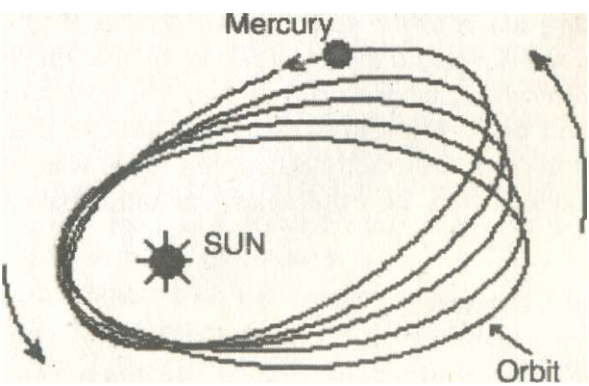

Fig. 28: Newtonian physics could not explain the precession of the orbit of Mercury.

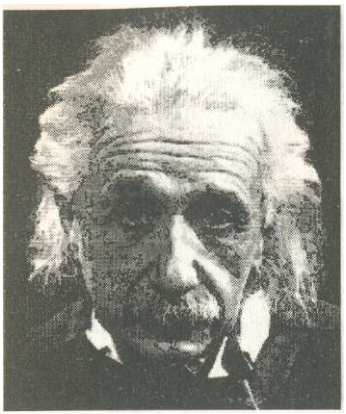

Fig. 29: Albert Einstein, whose theory of relativity changed our ideas about time and space.

gravitational influence of the other known planets.

Was there a yet undiscovered planet orbiting the Sun closer than Mercury? Initially some astronomers suggested exactly that; they thought that deviation might be caused by the gravitational pull of the unknown planet. For decades afterwards, astronomers searched for the supposed inner planet, which they named 'Vulcan', and many even claimed its discovery. But all reports of its discovery turned out to be false and astronomers agreed that Vulcan did not exist. Something else was responsible for the anomaly in Mercury's orbit.

The solution finally came in 1915, in the shape of the work of the German physicist Albert Einstein. While working as a patents examiner in the Swiss Patents Office in Berne in 1905, Einstein had published a revolutionary paper on the 'special theory of relativity' that altered our ideas of space, time, mass energy, motion and gravitation. It provided a new approach to the study of cosmos. In 1915, Einstein published his 'general theory of relativity' that finally solved the riddle of Mercury's orbit. When Mercury's orbit was calculated using Einstein's theory, the shift of the planet's perihelion could be exactly accounted for. It was one of the first successes of the new theory of gravitation based on relativity.

General Relativity

Why did Newton's theory fail? The basic problem with Newton's law of gravitation was its treatment of mass and inertia. Newton defined mass as a measure of a body's inertia; that is, its resistance to any change in motion. The higher

the mass of a body, the higher would be its resistance and the inertia. For example, a railway train has more mass and more inertia than a small car because it takes much more force to move a stationary train or to stop a moving one than to do the same to a stationary or running car.

According to Newton's law of inertia, if the same force is applied to two bodies of different masses, then it will produce a greater acceleration in the smaller body than in the bigger one. This principle holds true for a whole range of our everyday experiences. For example, a bowler applying the same force can throw a cricket ball much farther and much faster than he can throw a heavy piece of stone. But this relationship does not hold good in one particular case—if the acting force is the force of gravity. And this is where the trouble started.

As every student of science learns, if two bodies of different masses are dropped from the same height simultaneously in a vacuum, where there is no air resistance, then both should reach the bottom at the same instant—a phenomenon first postulated by Galileo in 1604. Galileo is said to have tested his hypothesis by dropping objects of different sizes from the top of the famous Leaning Tower of Pisa at the same instant of time. But there is no record of any such experiment having been tried out by Galileo. Such an experiment, if indeed done, would have been unable to prove anything, as air resistance would have made objects of different weights fall at different speeds. However, Galileo devised a better method of using an inclined plane to roll balls of the same size but made of different materials, to prove the point. Air friction offered little resistance to a rolling ball and so balls of different weights did indeed take the same time to reach the bottom.

The phenomenon of the simultaneous fall of two objects of different masses was dramatically demonstrated during the Apollo missions when a feather and a small hammer, dropped simultaneously by an astronaut on the Moon, were seen to reach the lunar surface together. The total

absence of air on the Moon did the trick. Of course, we can easily demonstrate the phenomenon on Earth by a simple experiment using a long evacuated glass tube with a large coin and a small feather inside. If the tube were suddenly turned upside down, both the coin and the feather would be seen to reach the bottom simultaneously. If air is now let in and the experiment repeated, the coin would fall faster than the feather because air resistance would be different for the two.

If objects of different masses fall at the same rate when dropped from a height, it would naturally mean that the force of gravity produces the same acceleration in bodies, irrespective of their mass. But such a situation would go against Newton's law of inertia, according to which acceleration produced by a force should be inversely proportional to mass. Newton got over this apparent anomaly by stating in his law of gravitation, that the attractive force between two bodies is proportional to their masses. That is, the force by which a material body attracts another body increases with the mass of the object it attracts. The heavier the object the stronger will be its pull of gravity. In other words, we have to presume that Newtonian gravity is always exerted in the precise degree necessary to overcome the inertia of any object. And that is why, according to Newton, all objects fall at the same rate regardless of their inertial mass. But this was too arbitrary an assumption, as it turned out later.

Einstein's theory of general relativity did not agree with Newton's theory in two important aspects. Newton considered the mass of a body to be constant, but Einstein's theory asserted that the mass of a moving body is by no means constant; it increases with its velocity relative to an observer. Einstein's theory also stated that no material object could ever reach the speed of light because if it tended to do so its mass would become very large, almost reaching infinity. Einstein's theory rejected the idea of gravitation being a force that can be exerted instantaneously over great distances, as

Newton had assumed in his law of universal gravitation. In Einstein's theory, gravitation was viewed as a property of space rather than as an attractive force between bodies. Further, it did not consider space and time as separate entities but as a single four-dimensional entity, which Einstein called 'space-time'. Einstein's theory did not reject Newton's theory altogether; it only showed that Newton's law does not apply exactly when we deal with speeds approaching the speed of light (over 300,000 kilometres per second), where the theory of relativity is more appropriately applicable. However, for situations that do not involve such fantastic speeds, Newton's law still holds.

Force vs Field

One of the fundamental postulates of Einstein's theory of general relativity is that, over a limited region of space-time, it is impossible for observers to tell whether they are undergoing uniformly accelerated motion or are in a gravitational field. For example, suppose a person is shut in a chamber without any door or window. As long as the chamber rests on the ground, the person will feel the pull of gravity. Now, if the chamber is transported to a location far from any mass-exerting gravitational pull, or is made to move at a constant speed, the person inside the chamber will not feel any pull of Earth's gravity and will float aimlessly, as astronauts do in a spacecraft. Now, if a force is applied (by means of a rocket engine, for example) to the chamber to impart to it a uniform acceleration in a given direction, the person inside will not be able to tell whether the chamber was stationary under Earth's gravity or it was being accelerated uniformly in free space. Einstein showed that it was not necessary to think of gravity as force acting at a distance. Instead, he described gravity in terms of its local effects on space and time, i.e. as the curved geometry of space-time, as determined by the distribution of matter and energy

Simply stated, Einstein's law of gravitation contains nothing about force. Rather it describes the behaviour of

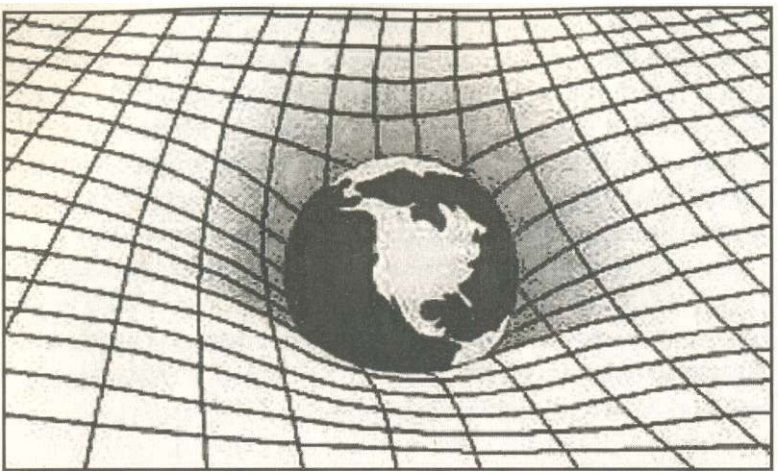

Fig. 30: A graphic representation of space-time distortion by mass.

objects in a gravitational 'field'. The planets, for example, move in orbits around the Sun not because the Sun attracts them, but because they follow different paths in a curved space. According to Einstein's theory, gravity is a distortion in the fabric of space caused by mass. As a result of the presence of matter, space becomes curved. The stars, planets and other celestial bodies simply follow the lines of least resistance among the curves.

When we talk of curved space in Einstein's theory we are actually talking of a four-dimensional entity called 'space-time' of which time is an integral part. We cannot visualise Einstein's concept of space-time using any physical analogy because it can be represented only by mathematical equations. Still, we can have an idea of what curved space looks like by considering a flat, flexible surface made of rubber stretched over a large wooden frame. If we drop an iron ball on the stretched rubber, the elastic surface will sag around the iron ball, making a depression on the surface. We can say that the space around the ball has become curved because of the presence of mass. A similar thing happens in Einstein's four-dimensional space-time

continuum in the presence of mass. If a glass marble is now rolled across the deformed surface of the stretched rubber, it will roll round and round in the depression, just like a planet orbiting the Sun. This is, of course, a very crude analogy with a two-dimensional surface, but it certainly helps in understanding the concept of curved space in Einstein's theory.

Einstein's general theory of relativity thus gave a completely new concept of gravitation. It not only provided a plausible solution to the riddle of Mercury's perihelion anomaly but also predicted two entirely new phenomena that were totally unexpected. First, it predicted that an intense gravitational field should slow down the vibrations of atoms causing a shift of spectral lines towards red. Secondly, it predicted that a strong gravitational field would bend even light rays. The first effect—the shifting of spectral lines under gravitational field—known as the 'Einstein shift', was detected in a class of small stars known as white dwarfs in 1925.

The verification of Einstein's second prediction of the bending of light rays by gravitational field came dramatically in 1919. That year, in photographs taken during a total eclipse of the Sun, stars were found to indeed shift position when light from them passed very close to the Sun. Comparing photographs of the same part of the sky taken earlier, when the Sun was not in the vicinity, it was found that stars, which ought to have remained hidden behind the Sun during the eclipse, were indeed visible in the photographs. Obviously light from these stars which were actually behind the Sun at the time the photographs were taken, had been bent by the gravitational field of the Sun, which led to their apparent shift in position in the photographs. More significantly, the degree of bending was exactly as predicted by Einstein's theory.

Einstein's theory of general relativity revolutionised our concepts of space, time and motion. And in doing so, it solved several cosmic mysteries and provided a new

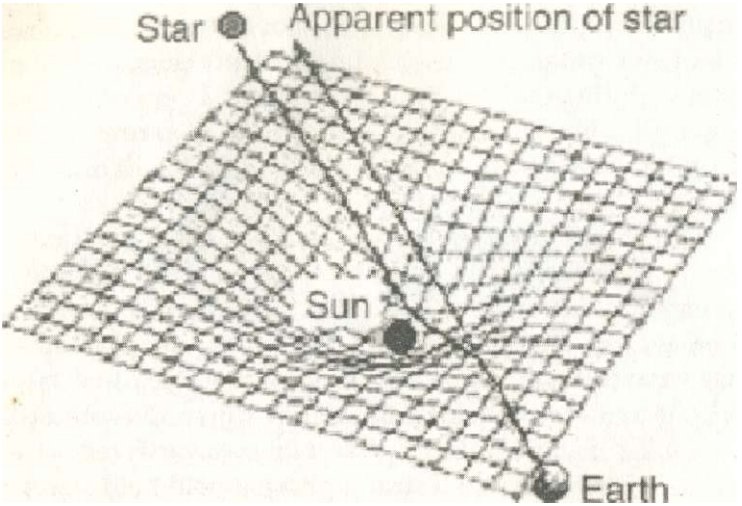

Fig. 31: Bending of starlight due to space-time distortion as predicted by Einstein's theory.

concept of gravity. Einstein's equations also anticipated the existence of bizarre cosmic objects, such as black holes—remnants of massive stars with gravitational fields so strong that not even light can escape from them. His equations also gave us the famous little formula of mass-energy equivalence ($E = mc^2$), that sums up all actions and creations in the universe. It is the unabated transformation of mass into energy as predicted by Einstein's theory that sustains the stupendously violent processes inside stars and galaxies and makes the cosmos like what we see it today. But the real significance of Einstein's work was realised only after technology became available for detecting radiation from violent processes going on in our cosmic neighbourhood, which revealed the real nature of the cosmic bodies that had remained unobserved in visible wavelengths.

10

AMAZING REFLECTORS

The invention of the telescope in early 17th century and its subsequent use for observing the night sky was just the beginning of a revolution in astronomy. Soon, more and more powerful telescopes were built and a chain of new discoveries about the Sun, Moon and the planets, indeed the universe at large, came forth. It was known to astronomers that larger the size of the objective lens the more would be the light-gathering power of the telescope and the brighter the image. But, the use of a lens as objective presented some problems. Images formed by single lens objectives showed colour fringes, which spoiled the quality of the image. Besides, it was quite expensive to fabricate very large glass lenses, which also became very bulky. But a new invention of the 17th century, made by the English genius, Newton, entirely changed the art of telescope-making.

The Versatile Reflector

Apart from his laws of motion and universal gravitation, Newton made significant contribution to optics—the science of light—that had a major impact on astronomy. He was the first to show that white light could be split into a range of colours by a glass prism, which forms the basis of optical spectroscopy used in determination of ine composition of the distant stars. Newton realised that it was this splitting of white light that led to the appearance of coloured fringes around objects when seen through a refracting telescope (refractor), a defect known as 'chromatic aberration'. The

edges of convex lenses behaved like prisms, splitting white light into its component colours, which produced the colour fringes around images. Modern refractors use a combination of lenses made of different kinds of glasses, known as 'achromatic lenses', to remove this defect. But Newton thought of a better and simpler alternative, of using a concave (parabolic) mirror instead of a convex lens of long focal length as the telescope objective. Since light of all wavelengths is reflected alike, no colour fringes are seen in an image produced by a mirror. Besides, grinding of a parabolic mirror is much simpler and cheaper than making an achromatic lens.

But if a mirror is used in place of a lens, then another problem arises. In a refracting telescope, as we all know, when light from a distant object passes through the objective lens, a magnified image of the distant object is formed on the other side of the lens, which is further magnified by the eyepiece. Here, while looking at the image the observer does not come between the objective and the object. But if a mirror is used as the objective, the image is formed on the same side and for viewing it the observer would have to stand between the object and the mirror. Obviously that would cut off all the light from the object! Newton found a simple solution to the problem; he placed a small plane mirror at an angle of 45^2 inside the prime focus, which deflected the light path to the side of the telescope tube, cutting off only a small fraction of the light falling on the objective. This arrangement made it possible to place the eyepiece in a side tube for convenient viewing, thus obviating any obstruction during viewing.

Newton's reflecting telescope, which he first made in 1668, was a revolutionary innovation in telescope design. It paved the way for larger and larger telescopes to be built, which saw a tremendous surge in our knowledge about the universe. It was because of the tremendous advantage the reflecting telescopes offer that no large refracting telescope has been built during the past hundred years. The world's

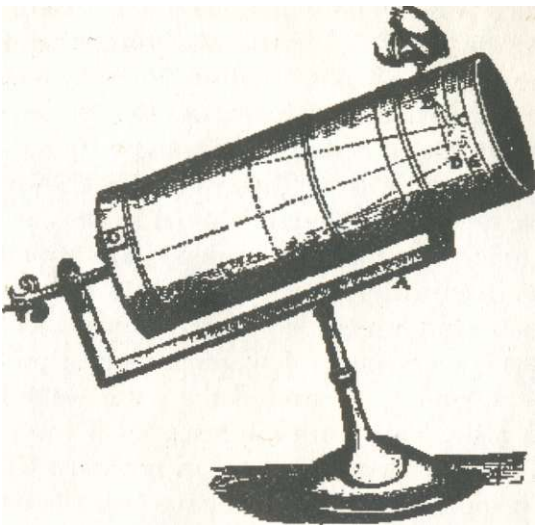

Fig. 32: Newton's reflecting telescope.

largest refracting telescope, with an objective diameter of 100 cm, was built more than a hundred years ago at Yerkes Observatory in the United States. The world's largest telescopes in astronomical observatories today and even the famous Hubble Space Telescope are all reflectors, although of different types.

Although Newton had built his first reflecting telescope in 1668, not many large reflectors for astronomical observation were built till the 20th century. The main problem was that large-diameter glass mirrors had to be thick for dimensional stability, which increased their weight tremendously and made them difficult to manoeuvre. Secondly, the front-surface silver coating easily got tarnished and needed frequent re-coating. Towards the end of the 1930s, two new discoveries emerged that revolutionised telescope making. The first was a method of depositing aluminium, rather than silver, on to glass mirrors. This produced a coating that was much more durable than silver and required less frequent re-coating. The second was the arrival of a new glass called

Pyrex, which was not only much less sensitive to temperature than ordinary glass, but was also tougher and could be cast as a hexagonal cellular structure that reduced its weight compared to a solid disc by half (*Plate IV).* No wonder, telescope sizes increased rapidly, beginning with the 2.5-metre reflector at Mount Wilson Observatory in USA in 1904, to the 5-metre reflector at Mount Palomar in USA in 1950, and a 6-metre reflector at the Zelenchukskaya Astrophysical Observatory in southern Russia. Today, thanks to new techniques of computer-aided telescope guidance and electronic image processing, a new generation of multi-mirror telescopes is coming up around the world—the largest of them being the Very Large Telescope of the European Southern Observatory at Paranal in northern Chile (*Plate V).* When completed, the VLT will have four telescopes, each

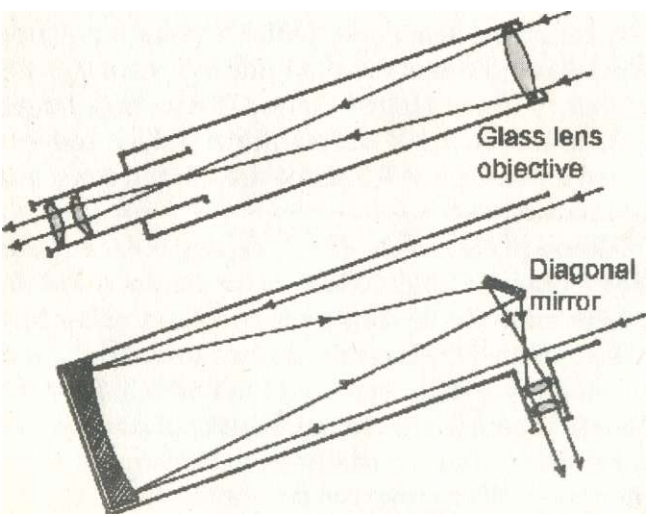

Fig. 33: Different types of astronomical telescopes. In a refractor, a glass lens is used as objective whereas a reflector uses a parabolic mirror as the objective.

with a mirror diameter of 8 metres. The combined effective diameter of the VLT will be 16 metres, the largest in the world.

For a Wider View

Astronomical studies in the early 20th century were mostly confined to photographic methods to record images of astronomical objects at the focus of the telescope. However, most telescopes of those days, which used parabolic mirrors as objective, could cover only a tiny fraction of the sky; most had a field of view no larger than about 1^2 across. The breakthrough came in the 1930s, with a design developed by Bernhard Schmidt in Germany, who used a spherical mirror and a transparent 'corrector plate', which vastly increased the field of view. The first Schmidt telescope, completed in 1930, had a field of view as large as 16^s across. At the same time, photographic plates also became progressively more sensitive to an ever-widening range of colours. A 1.2-metre Schmidt telescope at the Hale Observatory on Mount Palomar in USA was used in the 1950s for a photographic sky survey, which still remains the standard reference atlas of the sky of the Northern Hemisphere.

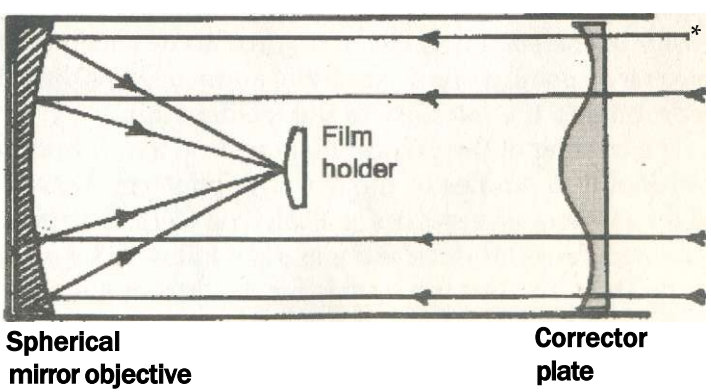

Fig. 34: A Schmidt telescope uses a spherical mirror and a corrector plate and can cover a much wider area of the sky.

Photographic techniques gave astronomers two distinct advantages. Firstly, photographic images provided a permanent record of the celestial objects for later comparison, and secondly, they made it possible for astronomers to see much fainter objects than they were able to observe visually. However, despite its advantages, the photographic method had its own limitations. The photographic emulsion did not show a linear response to the intensity of light falling on it if the intensity was very low. As a result, photographs of very faint objects not only took a very long time to record, but also did not always bring out the subtle differences in brightness of faint objects. Fortunately for the astronomers, help was already on way, in the shape of electronic light detectors, which made use of the phenomenon called 'photoelectric effect'.

Photon Power

The photoelectric effect, discovered by Albert Einstein in 1905, soon came to be used in a wide variety of detectors, the simplest of which was the photocell. In this device the incident light fell on a sensitive surface, called the 'photocathode', housed within an evacuated glass tube. The ejected electrons travelled across the evacuated space to a collecting electrode, also sealed within the evacuated tube. The intensity of the stream of electrons produced, which could be measured using a highly sensitive ammeter, was directly proportional to the intensity to the incident light.

The coming of the photocell opened up a new horizon in astronomical studies of the sky. The photocell was first used for astronomical studies in 1924, by a German astronomer named Paul Guthnick and was soon followed by others to study the stars. But the signals received from the photocathodes, except for the very bright stars, were too faint to be measured. The solution of the problem was found in the form of what came to be known as the 'photomultiplier tube'.

The photomultiplier tube is an enhanced version of the

phototube, with a series of electron-emitting plates (electrodes) that act as electron multipliers. When light hits the first photocathode, electrons are emitted. These electrons are accelerated towards the second electrode, which in turn ejects more electrons that move towards the third electrode, and so on. This process of multiplication is continued for several more stages till a flood of electrons are received at the anode. Frequently, magnification of a million times in the flow of electrons is achieved in a photomultiplier tube. The output is sent to a recorder or a digital storage device to produce a permanent record. Despite its high sensitivity and linear relationship between the number of electrons released and the intensity of light falling on it, however, the photomultiplier tube had a major disadvantage. Unlike a photographic plate, the photomultiplier tube could be used to record only one object at a time.

A better solid-state device, known as the 'charge-coupled device' or CCD, which made its appearance in the 1980s, has today replaced the photomultiplier tube. It uses a light-sensitive material on a silicon chip, arranged in two-

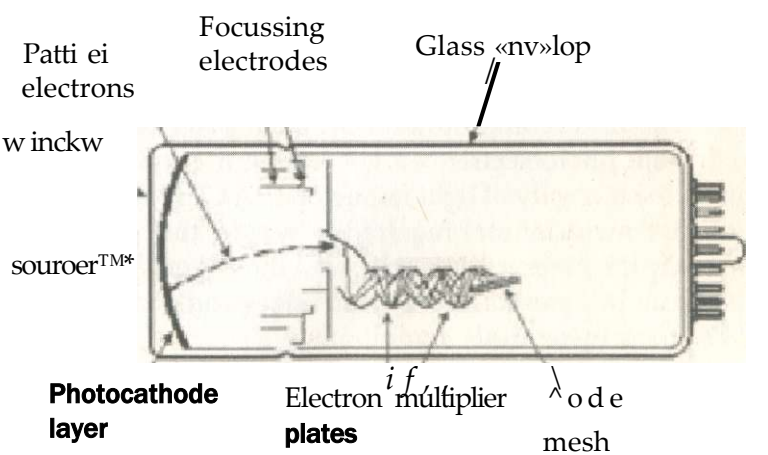

Fig. 35: A photomultiplier tube uses a series of plates to increase the number of electrons emitted to amplify the signal.

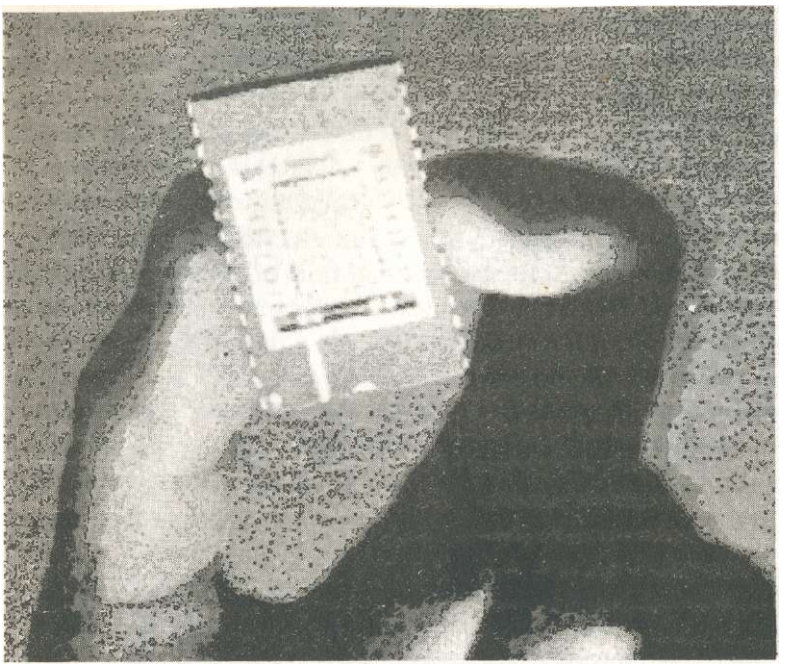

Fig. 36: A charge-coupled device is a hundred times more sensitive than photographic film.

dimensional arrays of tiny picture elements, or pixels, which can receive an image over a much larger area than is possible with a photomultiplier tube. Each pixel acts as a tiny solid-state photoelectric cell generating a current depending on the intensity of light falling on it. A CCD also contains integrate microcircuitry required to transfer the detected signal along the pixels and thereby scan the image very rapidly. Pixels can be assembled in various sizes and shapes, an 800 x 800 array being quite common.

The main advantage of the CCD is its extreme sensitivity. It is 100 times more sensitive that the photographic plate and so has the ability of recording images of fainter objects with very brief exposure. Another positive feature of the CCD is that the detector material may be altered to

provide more sensitivity at different wavelengths. The images can also he processed electronically to bring out better contrast and colour. Today most large observatories use CCDs to record data electronically (as do the new digital cameras, which don't use a film). CCDs also provided a reliable mode of recording and transmission of images taken from space to ground stations. The Hubble Space Telescope with a 2.4-m mirror, which was launched in 1990, carries CCD detectors that have sent back thousands of images of solar system planets and deep space objects, which are of unprecedented quality.

Even with very powerful telescopes, ground-based astronomical observations are basically restricted to the visible wavelengths because the Earth's atmosphere cuts off most other radiations such as infrared, ultraviolet, X-rays and gamma rays from the sky. Although radio waves can pass through the atmosphere, until the 1930s no one ever thought of looking for radio waves from space, till Karl Jansky and Grote Reber of the United States discovered the radio 'window'. It immediately opened up an entirely new vista in astronomy.

10

THE RADIO SKY

In science, new discoveries are often made by chance, only because of the sheer inquisitiveness of a few individuals who refuse to give up. A remarkable breakthrough in the way we observe the universe also came about in the same manner in the 1930s, and radio astronomy was born. With that discovery, astronomers had yet another window through which they could observe the cosmos, and the view turned out to be astounding. Strange cosmic objects and violent processes going on in the far reaches of the cosmos could be observed for the first time.

Beyond Visible Light

For thousands of years, our knowledge about the cosmos remained limited to what we could see with our naked eye or through the optical telescope; that is, whatever we could observe in visible light. Early astronomers like Aryabhata, Copernicus, Tycho Brahe, Kepler, and Galileo—all did their pioneering work in astronomy by painstaking visual observation of the sky, spread over years. Later, photographic and spectroscopic techniques were used to extend the capability of the optical telescope manifold, bringing to light new facts about the cosmos. The knowledge gained through visual and photographic observation of the planets, stars and galaxies helped astronomers solve many of the cosmic riddles, like the nature of the planets and their moons, the structure of the Milky Way and craters on the Moon. Although no one realised it at that time, a large part of the

cosmos still remained unobserved and unknown, as it was beyond the range of the human eye or the optical telescope. A whole new range of cosmic phenomena that did not emit radiation in the visible range waited to be explored.

As we know today, visible light is a form of electromagnetic radiation and makes up only a very small part of the electromagnetic spectrum. The human eye is sensitive to only this limited range of wavelengths—corresponding to the colours red to violet. That is why our eyes cannot perceive radiation outside this range, which comprise the whole range of wavelengths from infrared to radio waves beyond red, and from ultraviolet to gamma rays beyond violet. The difference between visible light and the rest of the electromagnetic spectrum lies only in their wavelengths. Radio waves have relatively longer wavelengths while gamma rays have much shorter wavelengths compared to visible light. But, as we all know, radio waves can be received by using special antennas. In fact, all radio receivers work by receiving radio waves using an antenna and then separating the sound signal and amplifying it by using an electronic circuit. But the signals that we receive in our radio set are sent out by transmitters on Earth. Till the early 1930s nobody could imagine that radio signals could also come from outer space.

Radio Waves froiit Space

If the human eye could see in radio wavelengths, the universe would appear quite different from what optical

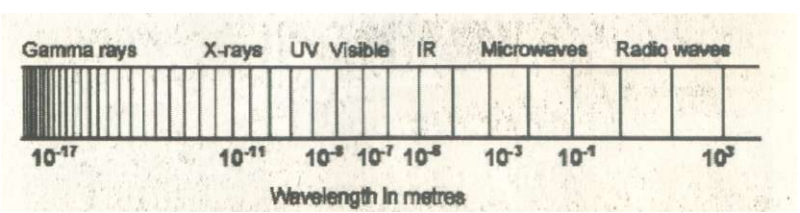

Fig. 37: Visible light constitutes only a tiny fraction of the electromagnetic spectrum.

telescopes reveal. The first source of radio waves from space was discovered in December 1931, during a routine study of static interference in radio transmissions, which is a common phenomenon and adversely affects the quality of the signals received. It was a time when a lot of studies were going on to find out better methods of radio communication. In the 1920s, amateur (ham) radio operators across the world were establishing communication links among themselves by using short-wave frequencies. Their experience showed that short-wave radio links could be used to carry intercontinental telephone calls, which might save the expense of laying undersea cables. But soon, such wireless telephone links were found to be plagued by atmospheric static noise caused by lightning and other atmospheric disturbances, which badly affected transmission quality.

It was at this time that a young radio engineer named Karl Jansky, working with AT&T Bell Laboratories in New Jersey, USA, was given the task of identifying the sources of short-wave noise. He built a highly directional antenna to

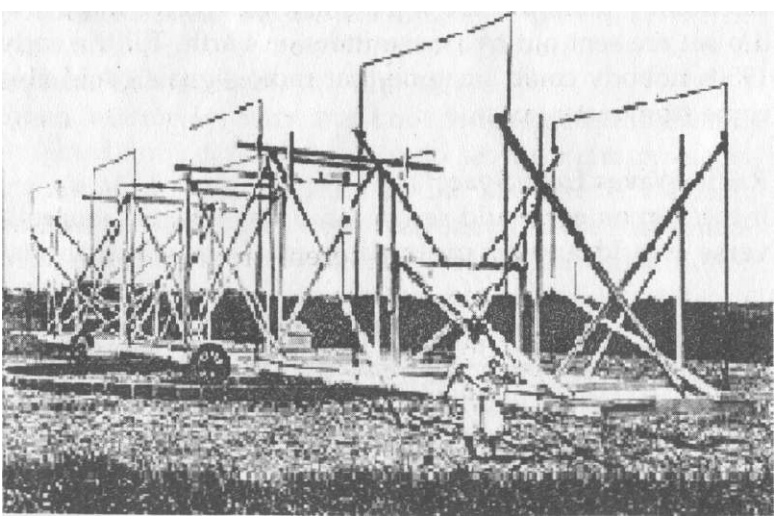

Fig. 38. The young radio engineer Karl Jansky opened up a new window on the universe by detecting radio waves coming from space.

work at about 22 MHz (i.e. capable of receiving radio waves having a frequency of 22 million cycles per second), and began to make systematic observations. Most of the noise he found was due to thunderstorms and other terrestrial causes. (Thunderstorms generate strong radio signals that produce the sharp crackling noise heard in medium-wave and short-wave radio broadcasts.) However, there was one source of a constant hiss for which no terrestrial source could be identified and which seemed to move from east to west in course of the day. Jansky followed the unknown source daily with his improvised radio antenna over a few days and was convinced that the radio waves were coming from a particular direction in space—from the direction of the constellation of Sagittarius. Indeed, what Jansky had found was radio noise emitted from the centre of our own Milky Way galaxy. He made this discovery in 1932 and announced his findings in 1933. His announcement was reported on the front page of the *New York Times* on 5 May 1933.

Jansky's discovery of radio waves coming from space was a real scoop, but surprisingly, it did not attract the attention of astronomers immediately. No one seemed to have immediately realised the tremendous potential of the new discovery in extending the limits of astronomy. To most professional astronomers, Jansky's discovery was a mere curiosity, and they did not follow up on it.

But there was one individual who took notice. In Wheaton, Illinois, USA[4] the news eventually reached Grote Reber, another radio engineer who was an avid ham operator. Reber had spent much time making long-distance contacts on the amateur short-wave bands. He had 'worked' all continents and 60 foreign countries. In those days, that. was quite an achievement, and it left Reber thinking, as he later wrote, "that there were no more worlds to conquer." When he read of Jansky's discovery, he realised that he had still a long way to go.

In 1937, Reber decided to take up Jansky's work as an opportunity and challenge. In his spare time, with his own

resources, he built for himself a steerable parabolic dish antenna (like the ones cable operators use to receive TV signals from satellites) in his backyard to scan the sky for radio signals. Reber's antenna was quite large, almost 10 metres in diameter. In an era when nobody had even dreamt of artificial satellites and television had not yet emerged from the laboratory, this antenna became a public curiosity, drawing amazed remarks from his neighbours.

But Reber's enterprise produced rich dividends. He hooked up his massive dish antenna to a sensitive radio receiver to make some remarkable recordings of cosmic radio waves. Using his set-up, Reber was able to precisely pinpoint the direction from which the radio signals earlier detected by Jansky were coming. It was indeed coming from the direction of the centre of our Milky Way galaxy.

The output from a radio telescope is usually in the shape of a contour 'map' outlining the areas of similar signal strength. (Modern radio telescopes use computers to produce false-colour images of the radio sky.) Reber continued his observations of the radio sky for more than a decade. His observations produced an amazing view of the universe. His radio 'maps' showed for the first time the startling differences between the 'visible' sky and the 'radio' sky. It marked the dawn of an entirely new branch of astronomy, which came to be known as 'radio astronomy'.

Radio Telescopes

Radio astronomy, or the study of the cosmos in radio wavelengths, soon became an established subject and radio telescopes, with large dish antennas, were discovering new phenomena in the universe. The first really large, fully steerable, radio telescope was completed in 1957 at Jodrell Bank, England (*Plate VII).* This telescope with a dish diameter of 76 metres is still used for a number of research programmes. The world's largest fully-steerable radio telescope is the 100-metre-diameter antenna operated by the Max Planck Institute for Radio Astronomy at Effelsberg, near

Bonn, Germany. The largest single dish radio telescope in the world is the 305-metre fixed spherical reflector operated by Cornell University near Arecibo in Puerto Rico (*Plate VIII).* The 305-metre antenna, built in a natural depression on a mountainside, has an enormous collecting area, but the beam can be moved through only a limited angle of about 20[a] from the zenith. The advent of faster computers has greatly helped in, not only processing the data collected by the large dish antennas, but also in steering them as well.

Since radio waves are much longer than light waves, the resolution of radio telescopes is rather limited. Radio astronomers therefore use an innovative method, known as 'radio interferometry' to study the finer details of a radio source. In radio interferometry, two or more moderate-sized radio telescopes, separated by several kilometres and linked together by cables, simultaneously study the same radio-emitting object. By electronically combining the signals received by each of the telescopes, it is possible to obtain a resolution that would otherwise need a dish antenna several kilometres in diameter (*see* p. 90).

There are several celestial objects that emit more strongly in radio wavelengths than in visible wavelengths. No wonder, radio astronomy has produced many surprises in the past half-century. Most of the familiar objects in the visible sky—the stars and the planets—have turned out to be invisible in the radio sky because they do not emit any radio waves. On the other>hand, some regions of the sky, where only faint stars are seen in visible light, have shown up as strong emitters of radio waves. One of the first discoveries made by using a radio telescope was that the Sun also emits radio waves. By 1950, several other sources of radio waves were identified. They included the famous Crab nebula, and two galaxies—M87 and NGC 3218. Later, radio telescopes enabled planetary scientists tv> discover intense radio emissions from Jupiter and to measure the temperature of all the planets. By the mid-1980s some 100,000 cosmic radio sources had been catalogued.

By studying the sky with radio and optical telescopes, astronomers could gain much more complete understanding of the processes at work in the cosmos. In addition, radar studies have shown that Venus, the surface of which always remains hidden behind thick clouds, rotates in the retrograde, or reverse, direction from that of the other planets. Radar measurements also have revealed the rotation of Mercury, which was previously thought to keep the same side towards the Sun. Utilising radio telescopes equipped with sensitive microwave spectrometers, researchers have discovered more than 50 separate molecules, including familiar chemical compounds like water vapour, formaldehyde, ammonia, methanol, ethanol, and carbon dioxide in space.

Powerful 'Star-like' Sources

But the really big discovery in radio astronomy came in 1960, when an entirely new class of astronomical objects never known before were detected in deep space. One of the first radio 'stars' discovered in 1960 that could be identified with a star in a photographic image, was called '3C 48'. It turned out to be an entirely new class of astronomical objects known as 'quasi-stellar radio sources' or quasars. These were point-like objects which appeared like stars in visible light but which also emitted extremely strong radio waves. A typical quasar was found to be no more than a light-year or two in size, but up to 1,000 times more luminous than giant galaxies with a diameter of about 100,000 light-years. Measurement of the red shift of the light from these objects showed them to be extremely distant, a typical distance being more than 10,000 million light-years. The question that puzzled astronomers was: What kind of energy source could produce the kind of brilliance that could be visible from such a large distance? To produce that kind of brilliance, quasars had to have an extremely powerful energy source and astronomers were convinced no star could produce such stupendous amounts of energy by conventional thermonuclear

reactions. By the end of the 1960s, radio astronomers had discovered more than 150 quasars, although not all of them were found to emit strongly in radio wavelengths. The nearest quasar, at a distance of only 783 light-years, was discovered in 1975.

The prodigious source of energy of quasars still remains an enigma, although some astronomers attribute it to black holes embedded in galaxies. (Black holes are remnants of very massive stars and are so massive and compact that not even light can escape their staggering gravity.)

Cosmic Time-keepers

By the end of the 1960s, with the discovery of quasars and several other radio sources in the sky, the tremendous potential of radio astronomy as an observation tool was proved beyond doubt and several refinements were already being tried out. Astronomers had designed instruments that could detect very short bursts of radio emission making it possible to study fast changes in cosmic radio objects. One astronomer who was trying out such an arrangement was Anthony Hewish, who was directing a research project at the Cambridge University Observatory in UK. He set up an array of more than 2,000 separate receiving detectors spread out in an array that covered an area of a little more than 1 hectare. In August 1967, one of Hewish's students named Jocelyn Bell detected a strange signal coming from a direction midway between the bright stars Vega and Altair that fluctuated with uncanny regularity The bursts were astonishingly brief, lasting only one-thirtieth of a second. No natural cosmic object could perhaps emit signals with such regularity.

The discovery of the pulsating signals immediately put the astronomical fraternity in a frenzy. Could the signals be artificial, sent out by some intelligent race elsewhere in the Galaxy? Such a possibility could not be ruled out altogether in the absence of an alternative explanation.

To find out the truth, Hewish and his team kept

monitoring the signals. A few days of observation convinced the scientists that the pulses were keeping time better than one part in a million, which implied that whatever the nature of the object, it was acting like a high-precision clock. After a month's observation it became clear that the signals could not be originating from a planet, because if it were so, the planet's orbital motion would have led to a systematic variation in the periodicity of the pulses, which was not the

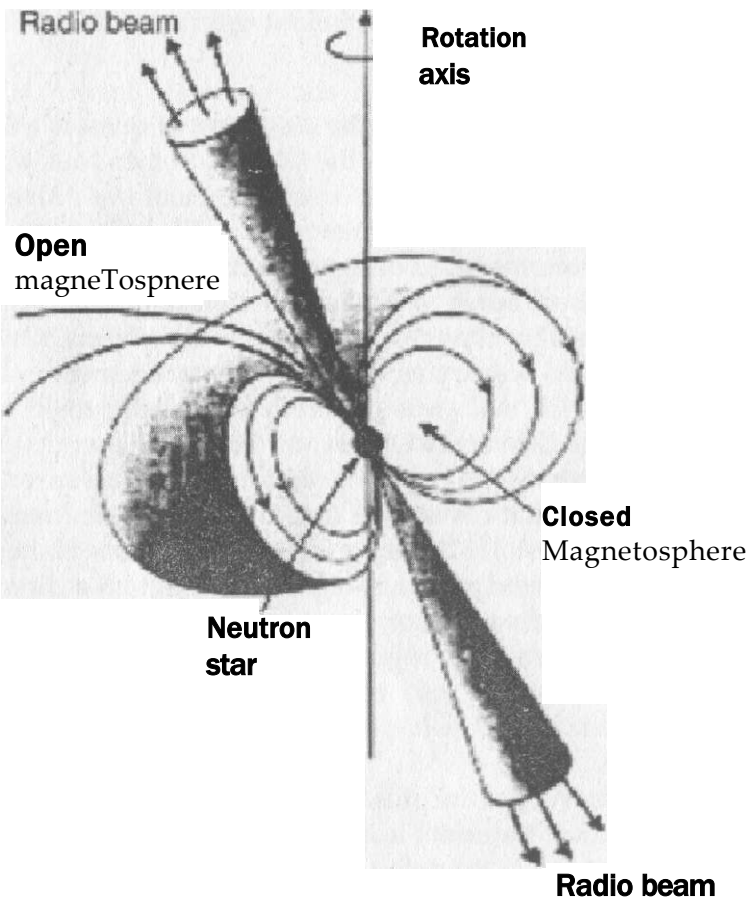

Fig. 39: A pulsar is a fast-spinning neutron star that emits radio waves like a beacon.

case here. Soon, many more such objects were discovered, putting at rest any possibility of their link with any alien intelligent civilisation. They were natural cosmic objects, the kinds of which were unknown before.

It did not take astrophysicists long to unravel the mystery. They soon came out with a plausible mechanism to account for the rapid pulsation of the radio signals from these strange cosmic objects. They suggested that the pulses were coming from fast-spinning remnants of massive stars made up entirely of neutrons. Neutron stars, as these objects are called, are produced when massive stars explode as supernova at the end of their life. These tiny cosmic objects are only a few kilometres in diameter but are extremely dense; they contain as much matter as our entire Sun. As they spin rapidly, they behave like cosmic 'lighthouses', sending out a radio beam that appears to flash rapidly when seen from Earth, just like a beam from a lighthouse or airport beacon appears to fluctuate to a distant observer. Thus, a fast rotating object could explain the rapid fluctuation of the radio signals. Astrophysicists had long speculated about the existence of neutron stars, but their discovery had to await the advent of radio astronomy. Because of the fluctuating radio signals sent out by fast-spinning neutron stars, they came to be known as pulsating stars, or 'pulsars' in short.

Relics from the Past

Quasars and pulsars were not the only objects discovered after the advent of radio astronomy; it also provided a much-awaited proof of the 'big bang'—the colossal event that is supposed to have brought this universe into existence in a primeval fireball, some 10,000 to 20,000 million years ago. In that titanic cosmic explosion, the universe began to expand, which has never ceased. As early as 1948, the famous American physicist George Gamow, in a paper he wrote with Ralph Alpher, made the remarkable prediction that, if indeed there were a big bang, the radiation accompanying this

very hot early stage must have cooled down with the expansion of the universe and should still be around today in the form of microwave radiation. It was predicted that the microwave background radiation should be characteristic of objects at a temperature of about 5K (that is, 5 degrees above absolute zero) and should be coming from all parts of the sky as a homogenous background.

The elusive all-pervading background radiation was eventually detected by two scientists of the Bell Telephone Laboratories, named Arno Penzias and Robert Wilson in May 1964. Here too, the actual discovery occurred by accident. While conducting experiments with the first *Telstar* communication satellite, Penzias and Wilson detected excess of radio noise that seemed to come uniformly from all parts of the sky The measured temperature of the radiation turned out to be 3K. It did not take long for scientists to infer that they had indeed stumbled upon the much sought-after cosmic background radiation. Most astronomers consider the discovery of this microwave background radiation as conclusive evidence in favour of the big-bang theory.

In 1989 a satellite called *Cosmic Background Explorer (COBE)* was launched to make detailed measurements of cosmic microwave background radiation (*Plate IX). COBE* data provided the first evidence of condensation of galaxies in early universe (*Plate X).*

Large Arrays of Antennas

As any astronomer would know, the resolving power of an optical telescope depends on the size of the objective lens or mirror. (The resolving power denotes the ability of a telescope to separate two close objects when viewed from a distance.) Larger the size of the objective the higher would be the resolving power. Resolving power is also a function of the wavelength of light; longer the wavelength the larger should the diameter of the objective be for better resolution. When dealing with radio waves, however, things become a bit tricky. As we all know, radio waves are more

than 10,000 million times longer than light waves. So, to have the same resolving power, a radio telescope ought to have a dish antenna 10,000 million times bigger! Of course, that is quite an absurd suggestion. But the size of the dish antenna indeed turned out to be a major constraint in radio astronomy, till radio astronomers came out with a bright idea. Rather than building a single giant antenna, they decided to use a large array of smaller dishes that together could act as a single antenna of enormous size. The largest array in operation today is the Very Large Array (VLA) radio telescope set up in New Mexico in the US (*Plate XI).*

The VLA, which went into operation in 1980, consists of 27 parabolic dishes that are each 25 m in diameter. Each of these dishes is mounted on a transporter that can be moved along rails laid out in an enormous Y pattern. Each arm of this pattern is about 21 km long. The radio signals recorded by the component dishes are integrated by computer, so that the entire array acts as a single radio antenna with a maximum effective aperture of 27 km; that is, the array behaves like a single dish antenna, 27 km in diameter, which would be impossible to build. This large aperture gives the VLA a resolving power equal to that of the best ground-based optical telescopes.

The world's largest radio telescope array is coming up in India. Known as the Giant Metre-wave Radio Telescope (GMRT), it is an array of 30 fully steerable parabolic dish antennas, each 45 metres'in diameter (*Plate VI).* Twelve of these are located in a compact central array, about 1 km (1 km in size. The remaining 18 antennas are placed along the three arms of an approximately Y-shaped configuration, with each arm extending to about 14 km from the array centre. Fourteen of the 30 antennas had been fully commissioned till the end of 2001—11 in the central array and three in the Y arms of the array When completed, GMRT will become the world's most powerful radio telescope operating in the frequency range of about 50 to 1500 MHz. The large size of the parabolic dishes implies that GMRT will have over three

times the collecting area of the VLA. The GMRT will be about eight times more sensitive than VLA because of the larger collecting area, higher efficiency of the antennas and a substantially wider usable bandwidth. Already some startling observations of supernova remnants and radio galaxies have been made, using the GMRT.

Indeed radio telescopes like the VLA and GMRT are revolutionising our ideas about the cosmos, showing it to be filled with violent activity, the like of which had been never known before. By being able to look back in time they are also throwing new light on the origin of the universe and its evolution over billions of years to its present state.

In the latter half of the 20th century, advances in instrumentation and improved observational techniques, especially space-borne detectors, have led to the discovery of cosmic sources that emit in infrared, X-ray and gamma ray wavelengths. Normally these wavelengths do not reach the ground as they are cut off by the Earth's atmosphere. Discovery of these objects has radically changed our view of the universe and of the cosmic phenomena going on out there. Astronomy no longer remains confined to ground-based observation of the star-filled night sky. It is much more exciting and challenging than astronomers of the past could ever have imagined it to be.

10

VIEW FROM SPACE

One of the biggest problems with ground-based observation of the cosmos is the fact that the Earth's atmosphere is opaque to a large part of the electromagnetic spectrum. As a result, radiation in infrared, extreme ultraviolet, X-ray and gamma ray wavelengths cannot reach ground-based detectors. So it is almost impossible to observe the sky in these wavelengths from the ground. The dawn of the Space Age in the 1950s came as a boon for astronomers, for it opened up enormous possibilities of observing the cosmos in wavelengths that are inaccessible from the ground.

X-ray Stars

Ever since the discovery of X-rays by the German physicist Conrad Wilhelm Roentgen in 1895, techniques have been developed for converting X-rays into visual images or into electronic signals that can be recorded. In medical science, X-rays are used only as a diagnostic tool, for imaging internal organs of the human body. In an X-ray machine, X-rays are produced, using extremely high-voltage electricity. So, nobody could possibly imagine that X-rays could also come from space. But it is now a fact. The detection of cosmic X-ray sources is evidence of the kind of energetic processes going on in the far reaches of the cosmos. This is again an example of how technology is changing our ideas about the universe we live in.

Unlike optical astronomy, the earliest records of which go back to several centuries, the history of X-ray astronomy

is just about five-and-a-half decades old. Before the invention of rockets, it was impossible to detect X-ray emissions coming from celestial objects from ground, as these radiations are totally cut-off by the Earth's atmosphere. The first X-ray pictures of the sky were taken in 1947, just after the end of the Second World War when the Americans launched a captured German V-2 rocket to a height of 160 km. The rocket carried an X-ray camera, which took 'pictures' of the Sun. The first pictures were not spectacular, but they did show that the Sun does emit some X-rays. The X-ray picture of the Sun showed the regions in the Sun's very thin outermost layer, called 'corona', which are extremely hot and actually emit X-rays. Later observations from the American orbiting space station *Skylab* showed the X-ray sources to be associated with other high-activity areas on the Sun, such as sunspots and solar flares. (It must be mentioned here that an X-ray picture of the Sun or any other astronomical object has no resemblance to the kind of X-ray shadow pictures we get of the human body in a hospital.)

Apart from the Sun, other sources of X-rays were subsequently discovered in space. Extremely hot gases in galaxies and star clusters are also known to give off X-rays, as do remnants of supernova explosions. Another copious source of cosmic X-rays are binary stars in which one of the components is a white dwarf, a neutron star, or even a black hole. All these sources emit X-rays by extreme acceleration of electrons—a process known as 'synchrotron' radiation (so called because this kind of radiation was first discovered in a high-energy particle accelerator, called 'synchrotron'). It was discovered that, when electrons are accelerated to very high speeds in a strong magnetic field, they emit radiation. The wavelength of this radiation depends on the speed of the electrons; the faster they move the shorter the wavelength becomes. If the speed is very high, the wavelength of the emitted radiation falls in the X-ray region.

After a massive star explodes as a supernova at the end of its life, electrons in the hot exploding gas also move

through the strong magnetic field at high speed, which leads to emission of X-rays. When a binary star has a white dwarf or a neutron star as one of the pair, and if the two are close enough, then the smaller, denser companion attracts material from the larger companion. As the gaseous material moves over to the very dense star, it suddenly becomes heated, strong enough to emit X-rays. In such cases the heating is sudden and intense, but does not last for long. These X-ray sources, therefore, flare up in less than a second and then fade out in a matter of minutes. If one component of the binary is a black hole, then gas and electrons stream into it from its companion star at extremely high speed. The material swirls very fast round the hole before falling in, leading to the emission of X-rays as synchrotron radiation. In fact, emission of synchrotron X-rays offers an easy way of detecting black holes, which are themselves invisible, as no light can come out of them.

The discovery of an X-ray source outside the solar system came in 1962, when an American *Ranger* spacecraft was on a mission to the Moon. It happened by chance to discover a very strong X-ray source in deep space. As it was discovered in the direction of the constellation Scorpius, the source came to be known as Sco X-1. The object was later found to be associated with a faint star and was emitting 1,000 times more energy as X-rays than at visible wavelengths. The discovery pointed to the fact that, besides our Sun, there were certairtly distant and more powerful X-ray sources as well.

The first satellite devoted to X-ray astronomy was launched in December 1970. Named *Uhuru,* the satellite detected more than 300 sources of X-ray emission in the sky during its two-year life span. One major scientific result of *Uhuru* was the discovery that a large fraction of the cosmic X-ray sources detected are binary systems, in which matter from a normal star is falling onto an extremely dense object, such as a white dwarf, a neutron star, or a black hole. These binary systems were found to emit almost 1,000 times

more energy in X-ray wavelengths alone than the Sun radiates in all the wavelengths. Later, as more refined techniques were developed and more advanced satellites were put into orbit, more celestial X-ray sources were discovered. Prominent among them are the Crab Nebula in the constellation of Taurus and Cyg X-1 in the constellation of Cygnus.

Chandra in Orbit

The most powerful space-borne observatory to study X-rays from the stars was launched in 1999 by the US National Aeronautics and Space Administration (NASA) and is expected to bring about a revolution in X-ray astronomy. It is named *Chandra X-ray Observatory (Plate XIII)* after the Indian-born Nobel laureate Subrahmanyan Chandrasekhar, who is known for his pioneering work on the evolution of stars. Its designers say, *Chandra* will unearth about 1000 new X-ray sources in every patch of sky the size of the full Moon.

An X-ray telescope is a very special form of telescope. An ordinary telescope would be of no use because the X-rays do not reflect off mirrors the same way that visible light does. Because of their high energy, X-ray photons would penetrate into the mirror in much the same way that bullets slam into a wall. In a similar way, just as bullets ricochet when they hit a wall at a grazing angle, so too will X-rays ricochet off highly polished mirrors. X-ray telescopes make use of this property of X-rays to focus them for getting images with high resolution. Mirrors used in an X-ray telescope are shaped like barrels, the inner surfaces of which are shaped and

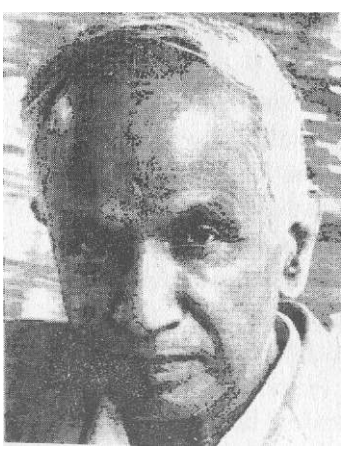

Fig. 40: The Indian-born astrophysicist Subrahmanyan Chandrasekar did pioneering work on the evolution of stars.

polished with extreme precision. They are aligned nearly parallel to the incoming X-rays, unlike the mirror in an optical telescope, the surface of which faces the incident light directly.

Compared to the earlier X-ray telescopes, the US$ 1.5 billion *Chandra X-ray Observatory* is a really big telescope. The length of *Chandra* is 13.8 metres. But what make *Chandra* really an advanced instrument are its mirrors that are used to focus X-rays. There are four sets of concentric barrel-shaped mirrors, which can bring X-rays from distant sources to a much sharper focus than ever possible. In other words, images received from *Chandra* will be much more detailed than any obtained so far. Sharper images would allow astronomers to see not only fainter objects but also finer details.

Another unique feature of *Chandra* is its orbit. Unlike all the previous satellites, including the Hubble Space Telescope, which is placed in a circular orbit, *Chandra* has been placed in a highly elongated orbit, which brings it to within 10,000 km of the Earth at its nearest approach and takes it

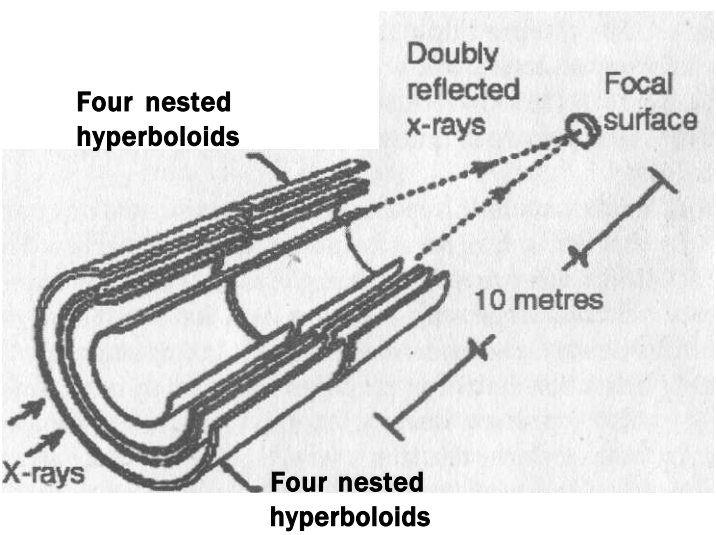

Fig. 41: The *Chandra X-ray Observatory* uses a special kind of barrel-shaped mirrors to focus x-rays from cosmic objects.

as far away as 140,000 km at its farthest point in orbit every 64.2 hours. At its farthest point *Chandra* will be fully one third of the way to the Moon!

In the field of X-ray astronomy, *Chandra* represents a new beginning. It has already revealed the presence of a black hole at the centre of our Milky Way Galaxy, ushering in the era of routine high-resolution X-ray imaging, and more important, of X-ray astrophysics. For the first time it is allowing astrophysicists to apply the tools of physics to high-energy astronomy. There is no doubt that Chandra's improved sensitivity will make possible more detailed studies of supernovas, black holes, and dark matter and turn a new leaf in our understanding of the origin, evolution, and destiny of the universe.

A Quark Star

In April 2002, NASA announced the discovery of an entirely new kind of star unknown before. The announcement, based on results from the *Chandra X-ray Observatory*, said the new star is possibly entirely made of fundamental particles called 'quarks'. The unique thing about this star is that it is only a few kilometres across but weighs more than our Sun. The star, called RX J1856 is about 360 light-years from Earth and if it were really made of quarks, it would be the first example of its kind.

Theoreticians had hypothesised the existence of quark stars in the 1980s, but none could be detected earlier. The star RX J1856 was previously thought to be a neutron star—formed when a large star explodes and its core collapses (neutron stars are also known as pulsars). At this stage, gravitational attraction between particles in an atom overcomes the electrical repulsion keeping them apart, fusing protons and electrons to form neutrons, which pack together at unimaginable density. A teaspoonful of neutron star would weigh a billion tonnes!

But *Chandra's* measurements suggested that, at just over 11 kilometres across, RX J1856 is too small to be a neutron

star, if current models are correct. Instead, neutrons and protons in the star may themselves have dissolved into an even denser mass of their constituent quarks, creating what astronomers call 'strange matter', in which the packaging of three constituent quarks in a proton or neutron breaks down, resulting in the densest form of matter theoretically possible. Here again, it was space technology that led to the discovery of yet another strange cosmic object, the existence of which would not have been imagined just two decades ago.

The Infrared Sky

Infrared radiation is a ubiquitous form of invisible electromagnetic radiation that is present almost everywhere. It was discovered in 1800 by the famous English astronomer William Herschel. In fact, all bodies above the temperature of zero degrees absolute (minus 273.16 degrees Celsius) give off infrared radiation. We can feel infrared radiation as heat when it falls on our skin. Many night vision devices used by the army to locate the enemy in darkness work by detecting the infrared radiation given off by the human body. But astronomers are interested in infrared radiation for another reason. The study of the sky at infrared wavelengths could reveal the location and character of cool material in the cosmos—material that is not hot enough to give off light—such as clouds of gas and dust in the process of forming stars or planets, or a star near the end of its life.

On Earth, infrared radiation is commonly associated with 'warm' objects, but celestial objects that emit in these wavelengths are actually a great deal cooler than objects that emit visible light. For example, very young stars, which may not be visible in optical telescopes, are very bright infrared sources. Besides, the longer wavelength allows infrared radiation to penetrate cosmic dust found around or between stars and galaxies, which are opaque to much shorter visible wavelengths, thus allowing astronomers to look behind impenetrable clouds of cosmic dust. The wavelength of

infrared radiation ranges from a few micrometres to a few hundred micrometres (one micrometre is one millionth of a metre). In fact, infrared radiation is longer than red light but shorter than microwaves. But, since the Earth's atmosphere cuts off infrared wavelengths longer than a few micrometres, it is impossible to carry out infrared observation of the sky from the ground.

Till the advent of satellites, astronomers had used numerous techniques to go beyond the Earth's atmosphere in order to have a better view of the sky in infrared wavelengths. Aircraft, balloons, and rockets were all used, but with only limited success. The first satellite exclusively devoted to infrared imaging of the sky was launched by NASA in January 1983. Called *Infrared Astronomical Satellite (IRAS),* it carried a 57-cm (27.4-inch) telescope cooled to a temperature of 2.5 degrees above absolute zero and was operated jointly by the United States, United Kingdom and the Netherlands *(Plate XV).*

An infrared telescope, like the one used in *IRAS,* is almost identical to an optical telescope because infrared radiation behaves almost like visible light and can be reflected by mirror or focussed by a convex lens. In fact, as any photographer knows, all modern photographic cameras can be used for infrared photography, using a special filter. This is exactly what is done in *IRAS.* The optics is the same as in any optical telescope; with a primary parabolic concave mirror and a secondary convex mirror for focussing the incident radiation. The only difference is that the whole system is cooled to a temperature of liquid helium (minus 268.9 degrees Celsius) to minimise the emission of infrared radiation from the telescope itself. After focussing the received infrared radiation, it is passed through filters that allow infrared radiation of only a few specific wavelengths to fall on the detectors placed at the focal plane. *(IRAS* operated at wavelengths of 12,25, 60, and 100 micrometres.) For detecting infrared radiation, solid-state semi-conductor photodetectors, arranged in arrays, was used in *IRAS.*

During its six-month sojourn in space, *IRAS* sent back a spectacular, new view of the cosmos that revolutionised our understanding of the solar system, nearby stars, the Milky Way and distant galaxies. Computer-processed visible images created from *IRAS* data revealed the sky to have a striking appearance at infrared wavelengths. For example, whole-sky images showed two bright intersecting bands, one associated with the plane of the Earth's orbit around the Sun (ecliptic plane), and the other with the plane of the Milky Way (*Plate XVI).* The glow from the ecliptic plane has been ascribed to the heating of interplanetary dust in the solar system by the Sun. The glow in the plane of the Milky Way is due to heated interstellar dust, but much cooler than that in the solar system. An interesting feature of the infrared view of the Milky Way is that while in visible light, the centre of the Milky Way galaxy (which lies in the direction of the constellation of Sagittarius) appears dark because it lies hidden behind a thick cloud of interstellar dust; in infrared it appears as the brightest region in the sky! This is because, having longer wavelengths, infrared radiation can penetrate the thick dust clouds that obscure the centre of the Galaxy in visible light.

The *IRAS* data have already helped astronomers uncover a few surprises lying hidden in cool cosmic matter ranging in distance from a few million kilometres to several million light-years away. Among them are galaxies that are almost 100 times more luminous at infrared wavelengths than in visible wavelengths'. In the area around the famous Great Nebula in the constellation of Orion, which has been known to be an active star-forming region, *IRAS* found an extensive complex of cold dust and gas highlighted by areas brightened due to heating by massive young stars embedded in the cloud or nearby. Only a small part of the *IRAS* data has been analysed so far. It may take several years to process the entire data gathered by *IRAS.* May be, we have still more surprises in store in the infrared sky!

Beyond Violet

Ultraviolet radiation was discovered by the German physicist Johann Ritter in 1803. He found that photosensitive crystals of silver iodide showed the maximum darkening when placed beyond the violet end of the spectrum. Our Sun releases copious amounts of ultraviolet radiation but most of it is absorbed in the upper atmosphere by the Earth's ozone layer. Astronomers had known that high-energy processes, especially very high temperatures, in cosmic bodies also release copious amounts of ultraviolet radiation. So, studies in ultraviolet wavelengths could provide new insights into cosmic processes. But, in this case too, the obstacle was the Earth's atmosphere. Very little ultraviolet radiation of wavelengths relevant for astronomy (roughly 100 to 4,000 angstroms; one angstrom being equal to 1/10,000,000,000th of a metre) penetrates the atmospheric blanket, and the solution lay in sending detectors beyond the atmosphere, carried in rockets or satellites. The first successful attempt to photograph the Sun in ultraviolet was made in 1946, when a rocket-borne camera did the job. Since the early 1960s, the United States and several other countries have placed in the Earth orbit unmanned satellite observatories for ultraviolet imaging of the sky.

Many new discoveries were made by the *International Ultraviolet Explorer* satellite, which was launched by NASA in January 1978. As a joint project of NASA, the United Kingdom and the European Space Agency, the satellite sent back data that supported the theory that a black hole with the mass of a thousand solar systems exists at the centre of our Milky Way galaxy. The data also provided evidence of gravitational lensing by a massive galaxy as being responsible for the so-called 'twin quasars' image. Here the strong gravitation field of the massive galaxy bends the light coming from the distant quasar, as predicted by Einstein's relativity theory, to produce the double image. The *IUE* also discovered that our Milky Way galaxy is surrounded by a halo of hot gases.

Gamma Rays from Space

As we have seen, the cosmos, when glimpsed through different bands of the electromagnetic spectrum, presents many contrasting views. And of all of them the gamma-ray astronomer's view may be the most exciting. Since gamma rays are the most energetic of the electromagnetic radiations, they provide an insight into the most violent, chaotic, and explosive processes going on in the far reaches of the universe. Gamma ray astronomy provides a unique view of the hottest, most energetic regions of the cosmos.

Gamma rays were named by the British physicist Ernest Rutherford in 1903. They are the most energetic among the three kinds of radiation given off by radioactive elements. In space, they are produced by violent processes taking place in the interior of galaxies. For example, gamma rays are produced when lighter elements are created by nuclear fusion in the interior of stars; in supernova explosions, where heavier elements are created. Gamma rays are also produced in processes involving the interaction of matter and anti-matter and of subatomic particles with other particles or with magnetic fields, matter or even photons. Many of these processes are believed to occur in the extreme conditions found in and around supernovas, black holes, pulsars and quasars. Although gamma rays are a highly penetrating form of radiation, they are readily absorbed in the Earth's thick atmosphere. So, ground-based observation is almost impossible, and observations have to be made from space.

Interestingly, the detection of gamma rays from space came about almost accidentally. In the late 1970s the United States had been launching Earth satellites to detect gamma ray emissions from nuclear testing. Surprisingly, these satellites instead discovered bursts of gammf rays from deep space. These occurred at a rate of one 01 two per day and typically lasted for a few seconds to a few minutes. But their source remained a mystery. Since then, several other spacecraft have been launched to probe gamma rays coming from

space. Among them was the *Compton Gamma Ray Observatory (GRO*), which was launched in April 1991 (*Plate XXI).* It carried instruments that are 10 times more sensitive to gamma rays than those on board earlier gamma ray satellites. By 1998, the *GRO* had detected more than 1,700 gamma ray bursts, distributed in a completely random pattern across the sky. But, because of the extremely short duration of the bursts, the *GRO* was unable to locate their position accurately.

In 1996, an Italian-Dutch satellite, called *BeppoSAX,* was launched into orbit. It was able to achieve a 50-fold increase in positional accuracy; that is, it could locate the source of the gamma ray bursts much more accurately than the GRO could. In December 1997, *BeppoSAX* detected the most powerful gamma ray burst till date, coming from a source located some 12,000 million light-years away. The powerful burst is believed to have come from the merger of two neutron stars. Theoretical calculations show that in the final seconds of such a merger, the brightness of the two stars together can exceed that of a billion galaxies, like the Milky Way, before they end up in the formation of a black hole.

The data sent back by *GRO* and *BeppoSAX* have revealed the cosmos in its most violent form that was beyond the imagination of astronomers only a few decades ago. This revelation has again been possible only through a systematic study of the cosmos, using the latest tools of technology that extended the limits of human skill to explore and understand the cosmos.

10

PLANETARY WORLDS

In the early 17th century the invention of the telescope dramatically changed our views of the planets; instead of mere bright points of light, they turned out to be much larger bodies, some with their own moon systems. As telescopes became larger and more powerful, greater surface details and other features of the planets came into view. Some were really fantastic. Jupiter had a large red spot and several moons in orbit around it; Saturn was surrounded by a majestic ring; Mars had white polar caps that changed with Martian seasons. Between 1781 and 1930 three new planets were discovered beyond Saturn. In 1978, a moon was discovered around the solar system's outermost planet Pluto. Our planetary neighbours were turning out to be really fascinating.

But these revelations were nothing compared to what came after space probes began studying the planets from close quarters. Till date, space probes have been sent to all the planets of our solar system except Pluto, and they have sent back a wealth of data and fabulous pictures that are once again changing our ideas about the planets. The pock-marked surface of Mercury; cloud-covered Venus; volcanoes, river valleys and gigantic canyons on Mars; turbulent clouds and amazing moons of Jupiter; majestic rings and moons of Saturn; rings of a rolling Uranus; and blue clouds of Neptune were all unknown before space probes caught them from close quarters. The new image of our solar family is turning out to be radically different from what we had known earlier.

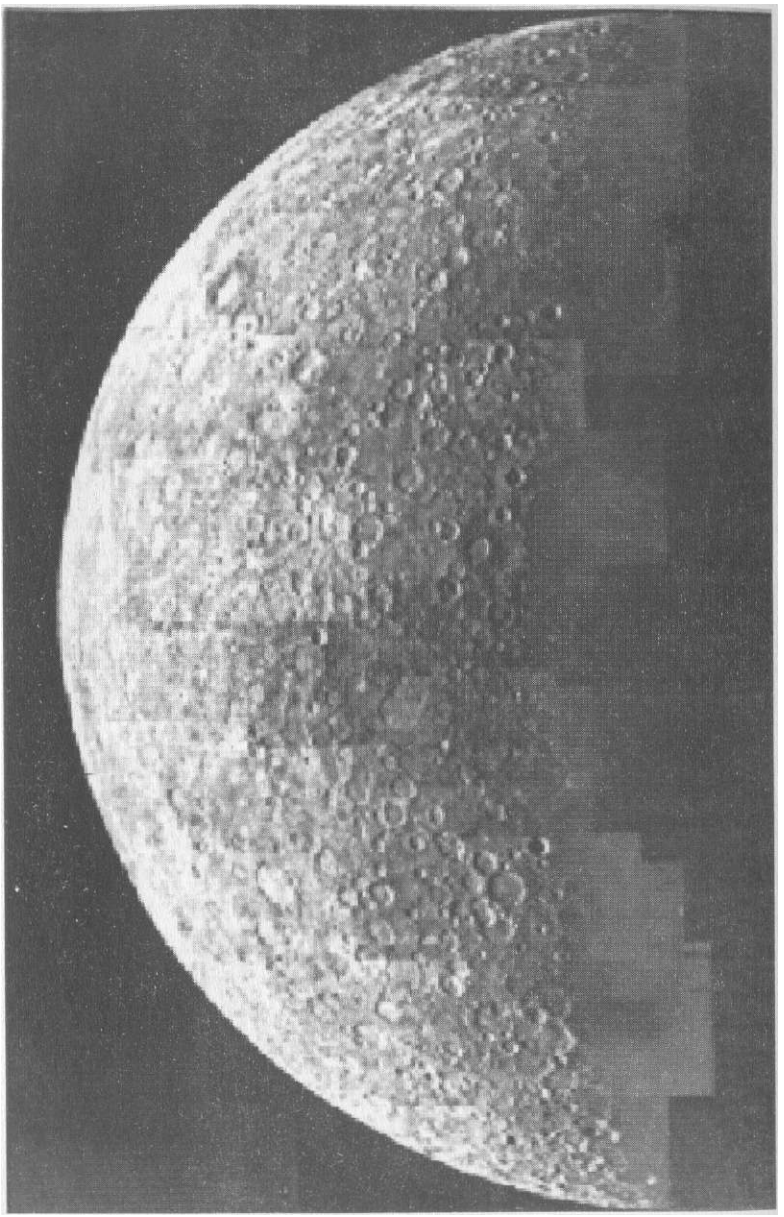

Fig. 42: Mariner spacecraft revealed Mercury's surface as almost like our Moon's - pockmarked with craters.

Seeing Close-up

One problem with observing the planets from Earth is the large distances that separate us. For example, the planets Venus and Mars are our nearest planetary neighbours. Even then, when closest to Earth, Venus is more than 40 million kilometres away and Mars is more the 56 million kilometres away. The other planets are much, much farther away—Jupiter, 628 million km and Saturn, 1277 million km. So, even with very powerful ground-based telescopes we can see the surface details only up to a point. Atmospheric turbulence and limitations of telescope optics limit the amount of details that can be seen. Soon after the Space Age dawned, astronomers started thinking of sending space probes to the planets. After all, if we could send space probes with cameras to within a few thousand kilometres of the planets, it could show much greater details than can ever be seen from the Earth. And this indeed turned out to be so.

Ground-based telescopic observations of the planets Mercury and Venus show almost no details of their surface. Mercury always remains so near the Sun in the sky that for most of the time it remains hidden behind the dazzling glare of the Sun. (Mercury is so elusive that many renowned astronomers, including Copernicus, have lived out their lives without ever seeing it!) Venus, on the other hand, appears so bright that no details of its surface can be discerned from ground-based observations. Only after space probes imaged them from near that the true nature of the surfaces of the two planets was revealed. The surface of Mercury turned out to be almost like our Moon's—pockmarked with craters, the largest of which is 200 km in diameter, with no atmosphere. Venus, on the other hand, was perpetually covered under a thick blanket of cloud; it was impossible to penetrate the cloud layer to see what lay below it (*Plate XXIII).*

Later space missions to Venus dropped instrumented capsules and studied the surface beneath its clouds from orbiting spacecraft using radar-mapping technique. Both

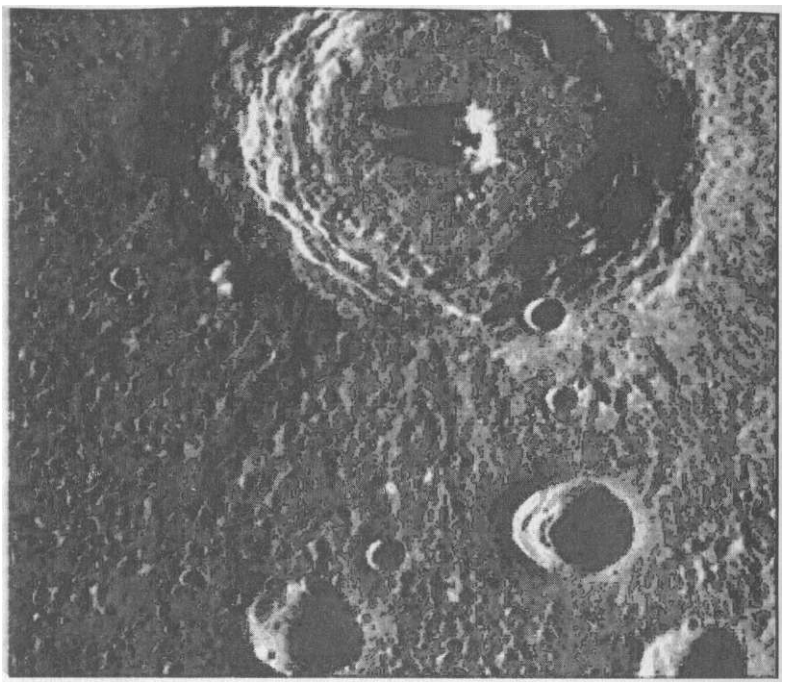

Fig. 43: Close-up of Mercury's surface showing striking similarity with our Moon.

techniques have brought out startling results. From data sent back by instrumented landers before they were destroyed by the corrosive Venusian atmosphere, the surface of Venus was found to resemble the classical picture of hell, with a surface temperature of a scorching 480ºC. Covered with clouds of corrosive sulphuric acid, the Venusian atmosphere is so dense that the surface pressure is of the order of 90 Earth atmospheres. From radar images sent back by the *Magellan* spacecraft, which orbited the planet between August 1990 and October 1994, the surface of Venus has been found to be covered with huge impact craters, volcanic craters and solidified lava flows (*Plate XXIV).* Many areas of Venus show colossal volcanic features that have been built up by successive overlaying of newer lava flows on older ones.

The Martian Enigma

Among the planets of our solar system none has aroused as much public interest and given rise to so many myths as the red planet Mars. For centuries astronomers had marvelled at the fuzzy red ball they saw in their telescope eyepiece and lavished on it their most fanciful dreams—of a planet inhabited by intelligent beings. Interestingly the myth of intelligent life on Mars arose not out of any scientific discovery but out of just the wrong interpretation of an Italian word. The story goes that, in August 1877, when Mars was closest to Earth, the Italian astronomer Giovanni Schiaparelli was observing the planet with his telescope. During his observations he noted what looked like fine network-like markings on the surface of Mars. He called them *canali,* which in Italian means 'channels'. But later astronomers misinterpreted the word to mean 'canals'—artificial structures meant to carry water for irrigation. In 1894, the famous American astronomer Percival Lowell added a new twist. He suggested that, since the 'canals' on Mars were shaped like straight lines, like man-made canals on Earth, they ought to be the work of intelligent beings. And thus was born the myth of intelligent Martians, which later gave rise to a spate of science fiction stories, including H.G. Wells's famous *War of the Worlds.*

Surprisingly, the possibility of the existence of life on Mars was taken quite seriously by astronomers and so, when space technology became available in the 1960s, plans were made to send spacecraft to Mars to make on-the-spot study of any life existing there. But flyby missions to the planet during the 1960s and early 1970s revealed the red planet as a desolate desert, just like Earth's deserts, with no water or vegetation. The photographs sent back during the missions showed vast canyons and massive dead volcanoes, larger than any on Earth. The extinct Martian volcano Olympus Mons, which is more than 25-km high and has a crater 80-km in diameter, is the largest volcano in the solar system *{Plate XXVI).* But Mars does not have any straight canals;

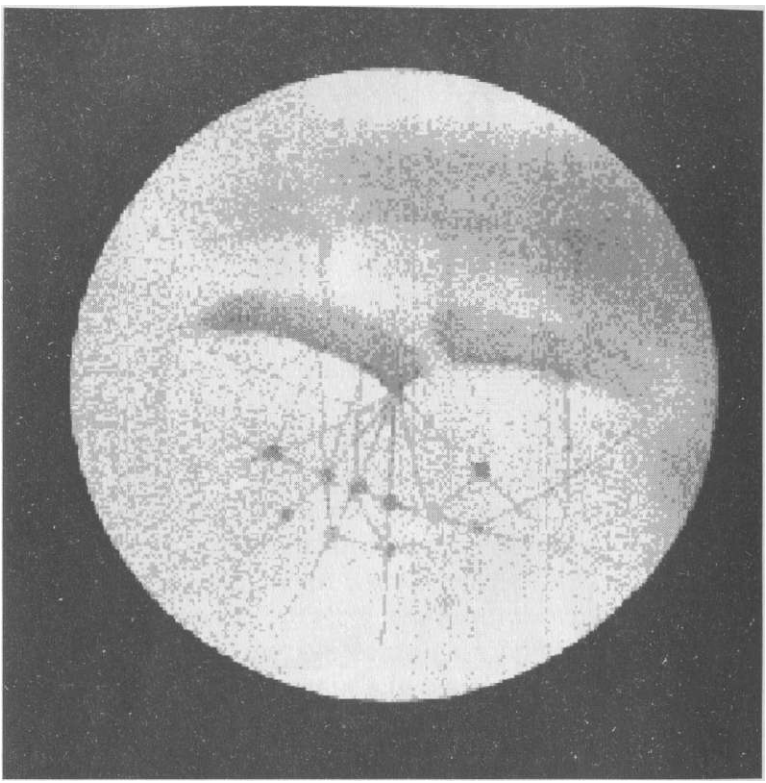

Fig. 44: Lowell's map of the surface of Mars showing a network of 'canals'.

only what appear like dried up, meandering riverbeds. Most important of all, none of the flyby missions could detect any sign of life on the red planet.

In 1976, two *Viking* spacecraft, equipped with instruments to test for signs of life, made soft landings on Mars and carried out chemical tests on Martial soil for biological reactions, but found none. However, the Vikings showed the iron-oxide-rich Martian soil to be really red-coloured, which gives the planet its nickname. In July 1997, another spacecraft named *Pathfinder,* which carried a remote-controlled robot vehicle called *Sojourner,* landed on Mars *(Plate XXVIII).* Data and pictures sent back by *Pathfinder*

startled scientists; the pictures showed extensive flood channels—evidence of copious flows of water on Mars in the distant past. But where all the water has gone no one knows as yet. The only water now remaining on Mars seems to be frozen in its polar caps. However, scientists are still debating whether microscopic life forms still survive under the Martian soil. Only future space missions may settle the issue.

The Planetary Giants

With a diameter of 143,760 km, Jupiter is the largest planet of the solar system followed by Saturn, which has a diameter of 120,420 km. Both the planets make interesting telescopic viewing. Even a low-power telescope with a magnification of 50x would show Jupiter as a small disc with two faint, dark cloud bands, and its four moons as tiny points of light. With larger telescopes a large red spot and as many as 13 moons orbiting it can be seen. The view of Saturn is equally fascinating. Although none of its moons is visible through a low-power telescope, its majestic ring system is clearly visible. Before the advent of space probes, 11 moons of Saturn were known. But the coming of the Space Age has totally changed our views of the two planetary giants.

The first spacecraft to fly past Jupiter was *Pioneer-10,* which sent back extraordinary images of the planet and mapped the planet's extensive magnetic field in 1973. But the real surprise came after two *Voyager* spacecraft (*Plate* XXDQflew by the planet in 1979. Not only were three new moons discovered, bringing the total number of Jovian moons to 16, but startling differences among Jupiter's four largest moons also came to light. For the first time active volcanoes were discovered outside our Earth—on Jupiter's moon Io, spewing sulphurous vapours 300 km upwards *(Plate XXXIII).* The surface of Europa was covered with ice, with a 'cracked-egg' appearance *(Plate XXXIV).* Solar system's largest moon Ganymede was found to be covered

with dark cratered areas having lighter grooved terrain (*Plate XXXV),* while the surface of Jupiter's second largest moon Callisto was extensively cratered, like our own Moon (*Plate XXXVI).* The *Voyagers* also found a thin dust ring around Jupiter, which cannot be seen from the Earth even with the most powerful telescopes. From close-up, Jupiter's Great Red Spot was found to be a huge swirling storm cloud that was more than twice our Earth in size. Its red colour was found to be due to the presence of phosphorus compounds. Since December 1997, another spacecraft named *Galileo* has been in orbit around Jupiter, sending back valuable data and images. *Galileo* data has shown that Jupiter's moon Europa may be having an extensive ocean of water beneath it icy crust. (Twenty-two tiny moons of Jupiter were discovered during 2001-2002, bringing the total number of moons of Jupiter to 39.)

After flying by Jupiter, both the *Voyager* spacecraft flew on for a rendezvous with Saturn. The *Voyagers* showed details of the ringed planet that are never visible from Earth. The images sent back by the *Voyagers* showed that Saturn's rings are divided into thousands of narrow ringlets that gave it the appearance of a grooved gramophone record (*Plate XXXVIII).* The *Voyagers* also discovered thin rings that appeared to be 'braided' around one another, and as many as seven new moons orbiting the planet, bringing the total number of Saturn's moons to 18.

The *Voyagers* not only discovered several new moons but also sprang a surprise regarding Saturn's largest moon Titan. For decades, astronomers had believed Titan (dia. 5,150 km) to be the largest moon in the solar system. But *Voyager's* data relegated it to second place, just behind Jupiter's moon Ganymede (dia. 5,262 km). The *Voyagers* found Titan to be surrounded by a thick atmosphere, which made it appear larger. Titan's atmosphere is surprisingly dense for so small a moon; at the surface its pressure is twice that of the Earth's atmosphere. Another spacecraft named *Cassini-Huygens* is now on way to Saturn to have a closer

look at the ringed planet and its largest moon Titan. Launched in 1997, *Cassini-Huygens* is expected to arrive in Saturn's vicinity in July 2004 and go into orbit around it. Later, in January 2005, it will drop an instrumented capsule on Titan to explore its atmosphere and surface. The ringed planet has never been studied so closely.

Remote Worlds

One of the biggest successes of space technology came in January 1986, when the spacecraft *Voyager* 2 swept within 82,000 km of Uranus, the first planet discovered by using modern scientific method. Twice as far from the Sun as Saturn, Uranus turned out to be a planet literally rolling on its side with its south polar region facing the Sun at the time *Voyager* 2 flew by (*Plate XXXIX). Voyager* photographs showed the colour of Uranus to be blue-green, probably due to the presence of methane. From Earth-based observations astronomers had known of nine thin rings and five average-sized moons in orbit around Uranus. *Voyager 2* discovered an additional ring and as many as 10 new moons orbiting the planet near the rings, bringing the total number of known moons of Uranus to 15. Close-up views of the large moons showed evidence of recent geologic activity, with the presence of fault canyons, mountains and cliffs.

The next and final destination of *Voyager 2* was Neptune, which orbits the Sun almost at the edge of the solar system. (In fact, between 1979 and 1999, Neptune was the outermost planet as Pluto's highly eccentric orbit brought it within the orbit of Neptune.) After flying through space for 12 years, *Voyager 2* flew by Neptune in August 1989. The encounter yielded several surprises, including what might be the fastest winds and the biggest geysers in the solar system. Winds on Neptune streak westward at a fantastic speed of more than 2,000 km per hour! Neptune was also found to have a 'Great Black Spot' almost resembling Jupiter's Great Red Spot (*Plate XL). Voyager 2*

discovered six previously unknown moons orbiting Neptune; only two were earlier known from Earth-based observations. But the most surprising discovery was that of a system of 'fragmented' rings around Neptune, which is unique in the solar system.

10

MEASURING THE COSMOS

One of the questions that had bothered astronomers for ages has been the size of the cosmos. How big is the universe? How far are the stars and the planets from us? There were no easy answers. Some historical accounts do suggest that some early astronomers were aware that the stars were like the Sun; they appeared point-like because they were very distant from us. But it was just a guess; the early astronomers did not have the means to measure stellar distances. The invention of the telescope in the early 17th century revealed the planets in a new form: they appeared as discs and not mere points of light, indicating that the planets were relatively closer. But the stars continued to appear as points of light. Obviously they were too far away to be resolved by telescopes.

Stars Bright and Faint

If we look at the sky on a moonless night, we will find there are bright stars and there'are faint stars. Even early astronomers had realised that distance had something to do with the brightness of stars as seen from the Earth. To give an analogy, if we look at the powerful headlight beam of a car from a kilometre away at night, it may appear dimmer than a battery powered torch, although in reality it is many times brighter than a torch. Similarly, some of the apparently dim stars may be actually very bright but may be appearing dim because they were far away from Earth, while some of the apparently bright stars may not actually be very

bright but may be appearing bright because they were closer to us. The problem is, unless we know how bright a star looks from near and how far it is, we cannot tell which is which.

Astronomers use two different measures to denote the brightness of a star. Its 'apparent magnitude' is a measure of the brightness as it appears from Earth, while its 'absolute magnitude' is a measure of its real brightness as measured from a standard distance of 10 parsecs (see *later).*

The 2nd century Greek astronomer Hipparchus was the first to devise a way of classifying stars on the basis of their apparent brightness (magnitude). He assigned numbers to the stars according to their apparent brightness, dividing them into six classes, or 'magnitudes'. The brightest stars were assigned magnitude 1 and the faintest ones magnitude 6. The brightest ones were taken as those stars which appeared first in the twilight after sunset, while those that were barely visible to the naked eye, even on the darkest and clearest night, were taken as the faintest. Hipparchus also drew up an important star catalogue, which was revised by Ptolemy for inclusion in his book, the *Almagest.*

In the days of Hipparchus and Ptolemy, the only tool for measuring the brightness of a star was the unaided human eye. Naturally, the grouping of the stars according to magnitudes was not quite precise. But today we have a better and more precise scale of magnitudes. According to this scale, a star of apparent magnitude 1 is 2.512 times brighter than a star of magnitude 2, which in turn is 2.512 times brighter than a star of magnitude 3, and so on. On this scale, very bright stars can even have a negative magnitude. For example, Sirius, the brightest star in the sky, has an apparent magnitude of -1.6.

While the apparent magnitude of a star could be measured by Earth-based observation, the knowledge of the distance was essential for estimating its absolute brightness. And measuring stellar distance was no easy task.

Measuring Parallax

A simple method of measuring very long distances is to measure the small shift in the position of a distant object against a background of still more distant objects when viewed from two separate positions. We can easily find out how it works by doing a simple experiment. If we hold a pencil vertically a little distance away from our eyes and look at it, first with the left eye and then with the right, the pencil will appear to shift from left to right, or vice versa, against objects which are farther away. If we increase the distance of the pencil from the eye, the shift becomes smaller and smaller. Now, if we know the distance between our eyes, then by measuring the apparent angular shift in position we can easily work out the distance of the pencil from our eyes.

Since the method just described makes use of the apparent change in the position of an object resulting from the change in the direction or position from which it is viewed, it is also known as the 'parallax method'. In this method,

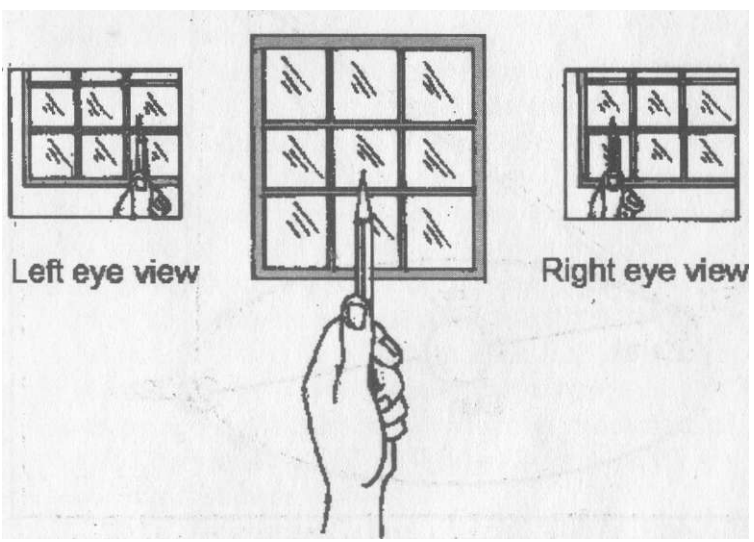

Fig. 45: A simple method of measuring parallax.

the apparent shift in the position of the distant object is expressed in terms of a small 'angle of parallax'. Apart from the distance of the object of which the distance is being measured, the angle of parallax also depends on the length of the baseline—the distance between the two positions from where the observations are made. The larger this distance the greater will the parallax be for the same distant object.

Early astronomers who tried to measure the parallax of stars did not succeed, as even the largest distance between two observation points on Earth was too small for such measurement. Even if the observations were made from the opposite sides of the globe, the distance separating them would be only about 12,700 km—far too small for a

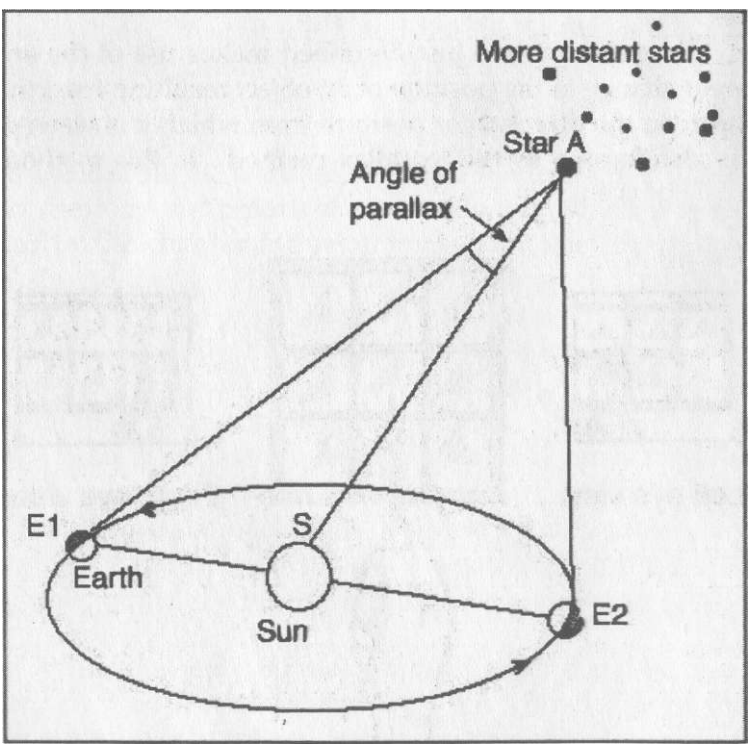

Fig. 46: Measuring the parallax of a star using the Earth's orbit as the baseline.

measurable stellar parallax.

The problem of a long enough baseline for parallax measurement was solved in a novel way by the German astronomer Friedrich Wilhelm Bessel. He decided to find out the parallax of stars by observing them on two different nights, six months apart. In other words, he made the observations from the opposite sides of the Earth's orbit, separated by a distance of 300,000,000 km. Bessel did not have luck with the first few stars he chose; they were too far away to show any measurable parallax. Finally, he was lucky, with a star named 61 Cygni in the constellation of Cygnus, which showed a distinct parallax. The parallax was very small—only about 0.3 seconds of an arc, but it was measurable. From this minute angle of parallax, and the known diameter of the Earth's orbit, Bessel calculated that the star 61 Cygni was 103,000,000,000,000 kilometres away; that is, it was 690,000 times farther away than the Sun! It was a remarkable discovery that would change our ideas about the scale of the cosmos forever. It revealed the stupendous scale of cosmic distances.

Cosmic Yardsticks

From Bessel's discovery it became obvious that for measuring distances on the cosmic scale, the commonly used unit of kilometres was too small. It was like measuring the distance between two cities in millimetres; it was too unwieldy. A more convenient yardstick for measuring cosmic distances is the speed of light. Light, as we know, travels with a finite velocity—a whopping 300,000 km a second. At this speed a beam of light travels a distance of 9,460,000,000,000 km in the course of a full year. Astronomers call this distance a 'light-year'. If we use this scale, the distance of 61 Cygni comes to about 11 light-years, which is more manageable than the previous figure. So light-year is a handy unit for measuring distances of stars.

Since distances of stars are usually determined by measurement of parallax, astronomers sometimes use

another, more convenient unit of distance, called the 'parsec'. A short form of the term 'parallax-second', it represents the distance at which the radius of the Earth's orbit would subtend an angle of one second of arc (1 second of arc is 1/3,600th of a degree). Thus, if the parallax of a star is 4 seconds of arc, its distance would be a quarter of a parsec. Inversely, a star with a parallax of 0.25 seconds will be 4 parsecs away. In terms of light-years, 1 parsec is equal to 3.256 light-years. For still larger distances, the unit of 'kiloparsec', which means a thousand parsecs, is used.

The parallax method turned out to be quite convenient for measuring the distances of nearby stars within the Milky Way galaxy. By the 1890s, the distances of several thousand stars had been determined by this method. But it could go no farther than about 500 light-years; beyond that, the angle of parallax became too small to be measured with reasonable accuracy.

Variability as a Clue

But scientists are an innovative lot. They are often able to make the most unusual use of a new discovery to solve an apparently insuperable problem. Here the discovery came in the shape of a new type of stars called 'Cepheids', which provided a new measuring rod for measuring stellar distances. As the name suggests, these stars get their name from the constellation of Cepheus in which the first star of its kind—called Delta Cephei—was discovered in 1784, by English astronomer John Goodricke.

Cepheids are a class of stars, which show a regular rise and fall in their brightness over a period of time. That is why they are called Cepheid variables. After Goodricke's discovery, Cepheids have been identified in other galaxies too. It was while studying these stars in a nearby galaxy outside our Milky Way, called the Small Magellanic Cloud, that astronomers stumbled upon a novel yardstick for measuring stellar distances.

In 1912, Henrietta Leavitt, an astronomer at the

Harvard Observatory in the US, was studying Cepheid variables in the Small Magellanic Cloud when she discovered a surprising correlation. She found that there is a direct link between the brightness of a Cepheid and the periodicity of its brightness change. To come to this conclusion, Leavitt made a clever assumption. Since all the 25 Cepheids she studied belonged to the same galaxy, she took their distances to be the same. It is like estimating the distance of a house in Delhi to a house in, say, New York. Although both Delhi and New York are large cities, we can safely take all the houses in that city to be at the same distance from a house in Delhi. After all, what is a difference of a few tens of kilometres in a total distance of several thousand? Leavitt's reasoning was, therefore, quite sound. What she discovered was that the brighter a Cepheid was, the longer it took to change from dim to bright to dim again. The less bright ones completed one cycle in much less time. The periods ranged from just short of a day to as long as nearly two months.

Thus, if indeed there was a correlation between the intrinsic brightness, as denoted by the absolute magnitude of a Cepheid and its period, and if its absolute magnitude were known, it would be simple arithmetic calculating its distance. For example, if two Cepheids had the same period but one of them appeared only one-fourth as bright as the other one, using Leavitt's correlation and the inverse square law, we can easily tell that the fainter of the two is twice as far away as the brighter one. The inverse square law states that the apparent brightness of a luminous object varies inversely as the square of the distance from the observer. So, if the distance is doubled, the object appears only one-fourth as bright.

But there still remained a snag. Unless we had knowledge of the absolute magnitude of at least one Cepheid, all that Leavitt's correlation could tell us was about the relative distances of two or more Cepheids, but not their actual distances.

In course of time, astronomers found a way to overcome this hurdle, too, by measuring the actual displacements in the position of some stars against the background over several years due to their 'proper motion'. These small displacements arise due to the real motion of groups of stars in relation to Earth and not due to simple parallax. After measuring the displacements of several star groups, including some that contained Cepheids, astronomers were in a position to determine their approximate distances. Once that was done, it was simple arithmetic to work out the absolute magnitudes from the observed brightnesses of those Cepheids. It was found that a Cepheid of absolute magnitude -2.3 had a period of a little less than six days. It was a breakthrough. For now, astronomers had another yardstick with which they could measure the depths of the universe, up to several million light-years.

Shifting Lines

Yet another tool for measuring galactic distances makes use of the phenomenon of the changing wavelength of radiation from a moving source. We are all familiar with the changing pitch of a train whistle as it approaches us from a distance and then passes by. The pitch first appears to rise and then fall as the train moves away. An Austrian physicist named Christian Doppler first gave an explanation of this phenomenon, which came to be known as 'Doppler effect'. In 1842, Doppler published a scientific paper in which he theorised that just as the pitch of sound from a moving source appeared to change to a stationary observer, so would the colour of light from a star, depending on the star's velocity relative to Earth. It was the French physicist Hippolyte Fizeau who, in 1848, gave an explanation for the shift in wavelength in light coming from a star and showed how it could be used to measure the relative velocities of stars that lie in the same line of sight. The shift in the position of spectral lines towards the red end of the spectrum came to be known as 'red shift'.

The red shift occurs because light waves from the stars that are moving away from us appear to become stretched, thus moving towards the red end of the spectrum (*Plate XLffl.* In 1929, the American astronomer Edwin Hubble, while analysing the spectra of distant galaxies found them all to be red shifted. This meant that all of them were receding away from us. Hubble conjectured that the galaxies were moving away from each other because the universe itself was expanding. He further proposed that the velocity of recession of the galaxies was proportional to their distances; that is, the farther they were the faster they would be moving away from us. He also gave a relationship between the two, which has come to be known as 'Hubble's law'.

Now astronomers had another tool for measuring cosmic distances. By measuring the red shift and using Hubble's law, it now became possible to measure distances of very distant galaxies. Since 1960s, the measurement of red shifts has enabled astronomers to measure the distances of the farthest cosmic objects ever discovered. Known as quasars, these strange objects have been found to be at distances of up to 10,000 million light-years. Since the age of our universe is between 10,000 and 20,000 million years, the measurement of red shift allows us to look at cosmic objects almost at the edge of our universe!

The *Nakshatras*

No.	*Nakshatra (European name)*	*Star*	*Magnitude*
1.	*Aswini* (Sheratan)	P Arietis	2.64
2.	*Bharani*	41 Arietis	3.68
3.	*Krittika* (Alcyone)	r| Tauri	2.87
4.	*Rohini* (Aldebaran)	a Tauri	0.85
5.	*Mrigasiras*	*X* Orionis	3.66
6.	*Ardra* (Betelgeuse)	*a* Orionis	0.50
7.	*Punarvasu* (Pollux)	P Geminorum	1.21
8.	*Pusya*	8 Cancri	4.17
9.	*Aslesa*	a Cancri	4.27
10.	*Magha* (Regulus)	*a* Leonis	1.34
11.	*Purva Phalguni* (Zosma)	8 Leonis	2.58
12.	*Uttara Phalguni* (Denebola)	P Leonis	2.53
13.	*Hasta*	8 Corvi	2.90
14.	*Chitra* (Spica)	a Virginis	0.98
15.	*Svati* (Arcturus)	a Bootis	-0.06
16.	*Visakha* (Zubenelgenubi)	a Librae	2.75
17.	*Anuradha*	8 Scorpii	2.32
18.	*Jyestha* (Antares)	a Scorpii	0.96
19.	*Mula* (Schaula)	*X* Scorpii	1.63
20.	*Purvasadha*	8 Sagittarii	2.70
21.	*Uttarasadha* (Nunki)	o Sagittarii	2.02
22.	*Shravana* (Altair)	*a* Aquilae	0.77
23.	*Dhanistha*	P Delphini	3.54
24.	*Satabhisaj*	*X* Aquarii	2.96
25.	*Purva Bhadrapada* (Markab)	a Pegasi	2.49
26.	*Uttara Bhadrapada*	y Pegasi	2.83
27.	*Revati*	*t,* Piscium	5.57

Recommended Reading

Asimov, Isaac: *Asimov s New Guide to Science,* Penguin Books, London, 1987.

Asimov, Isaac: *The Exploding Suns,* Michael Joseph, London, 1985.

Beatty, J. Kelly: 'In Quest of Mars', *Britannia Yearbook of Science and the Future 1990,* Encyclopaedia Britannica, Chicago, 1989.

Bose, D.M., Sen, S.N., Subbarayappa, B.V. (ed.): *A Concise History of Science in India,* Indian National Science Academy, New Delhi, 1971.

Brecher, Kenneth: 'New Eyes on the Gamma-Ray Sky', *Britannia Yearbook of Science and the Future 1995,* Encyclopaedia Britannica, Chicago, 1994.

Cornell, James and John Carr (ed.): *Infinite Vistas,* Charles Scribner's Sons, New York, 1985.

Couper, Heather: *The Planets,* Pan Books, London, 1985.

DeVorkin, David (ed.): *Beyond Earth,* National Geographic Society, Washington, D.C., 2002.

Goodman, Susan: *Spacefacts,* Oxford University Press, Oxford, 1993.

Hamilton, John: *They Made Our World,* Broadside Books, London, 1990.

Hawking, Stephen: *The Universe in a Nutshell,* Bantam Press, London, 2001.

NASA: *To the Edge of the Universe,* Bison Books, London, 1986.

Rao, S. Balachandra: *Indian Astronomy,* Universities Press, Hyderabad, 2000.

Sagan, Carl: *Cosmos,* Futura Publications, London, 1981.

Sidharth, B.G.: *The Celestial Key to the Vedas,* Inner Traditions, Rochester, 1999.

Stone, Edward C.: 'The Journeys of the Voyagers', *Britannia Yearbook of Science and the Future 1991,* Encyclopaedia Britannica, Chicago, 1990.

Trefil, James: *Other Worlds,* National Geographic Society, Washington, D.C., 1999.

Veverka, Joseph: 'Demystifying the Mystery Planet', *Britannia Yearbook of Science and the Future 1993,* Encyclopaedia Britannica, Chicago, 1992.

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Plate I: The Stonehenge, built around 3,100 B.C., consists of concentric circles of standing stone and was one of the earliest astronomical observatories of the world.

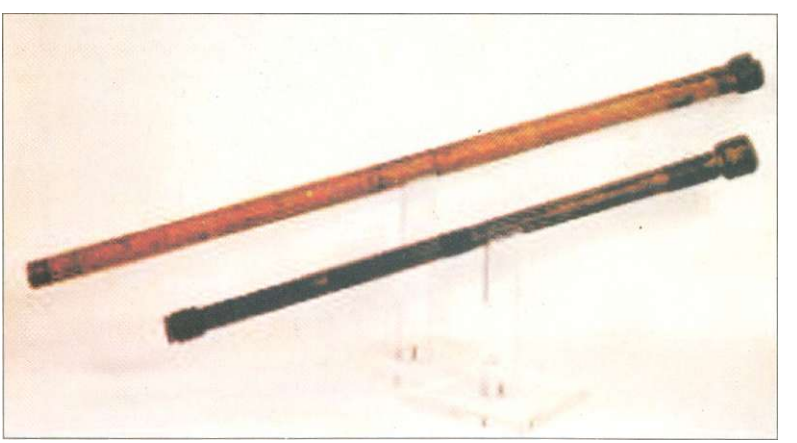

Plate II: Galileo built his own telescopes capable of magnifying 20 times, almost as good as today's amateur telescopes.

Plate III: Isaac Newton was one of the greatest figures in the history of science.

Plate IV: Pyrex glass allows mirrors to be cast as a hexagonal cellular structure that reduces their weight compared to a solid disc by half.

Plate V: The Very Large Telescope of the European Southern Observatory at Paranal in Chile comprises four telescopes, each with a mirror of diameter 8 metres. With a combined effective diameter of 16 metres, VLT is the largest optical telescope in the world.

Plate VI: An array of 30 fully steerable parabolic dish antennas, each 45 metres in diameter, the Giant Metre-wave Radio Telescope (GMRT) will be the largest radio telescope array in the world.

Plate VII: The first really large, fully steerable radio telescope was completed in 1957 at Jodrell Bank, England.

Plate VIII: Built in an enormous natural depression on a mountainside, the Arecibo radio telescope, with a 305-metre fixed spherical reflector, is the largest single-dish radio telescope in the world.

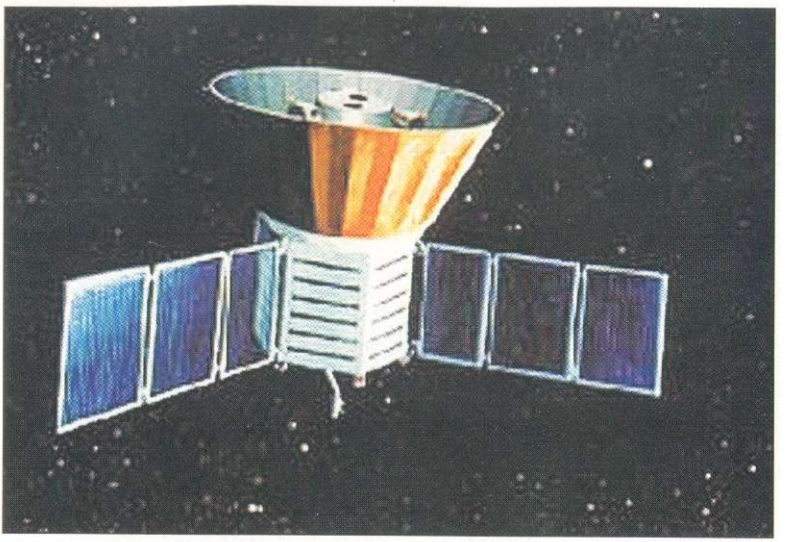

Plate IX: The *Cosmic Background Explorer (COBE*) was launched in 1989, to make detailed measurements of cosmic microwave background radiation.

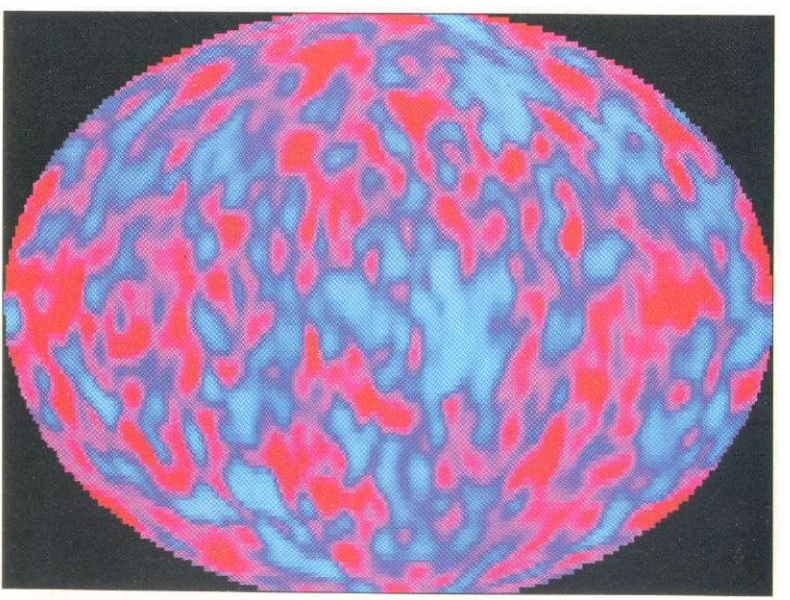

Plate X: COBE data provided the first evidence of condensation of galaxies in early universe.

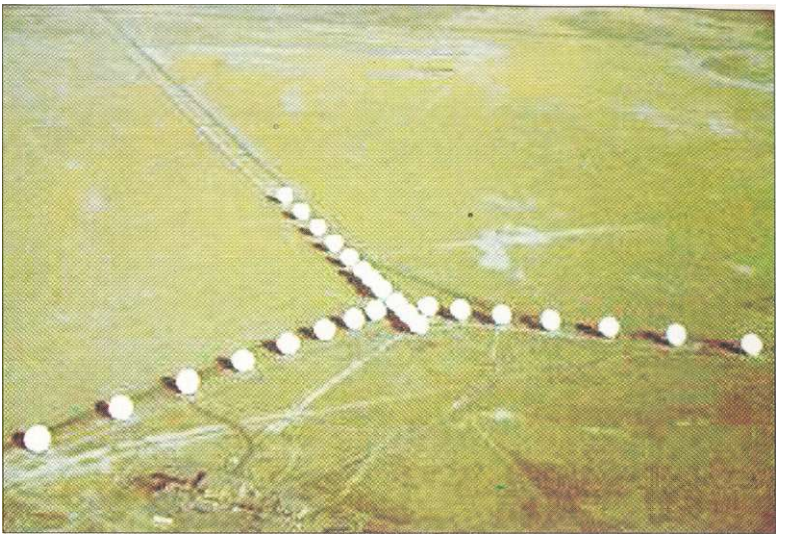

Plate XI: The largest array of radio antennas in operation today is the Very Large Array (VLA) radio telescope set up in New Mexico in the US.

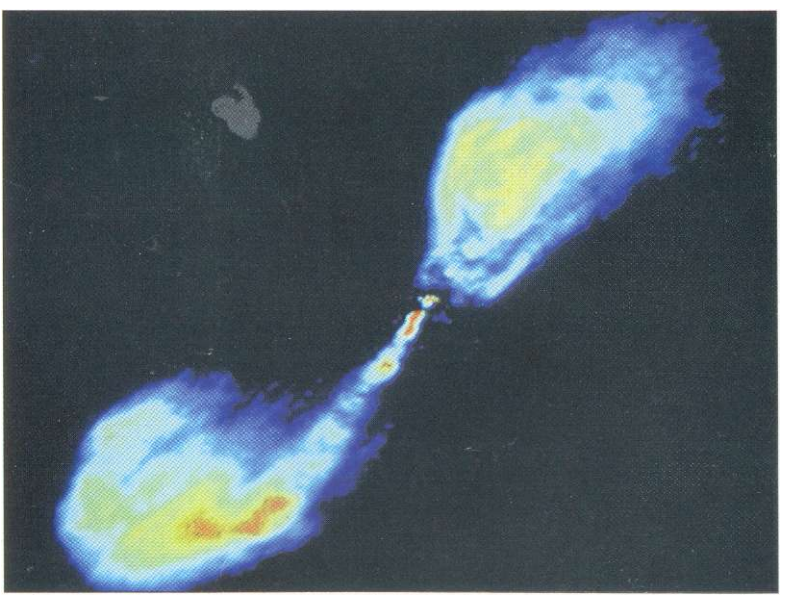

Plate XII: VLA discovered radio emission coming from the jei of the quasar 3C273, which appears in false colour in the image.

Plate XIII: The *Chandra X-ray Observatory* is the most powerful space-borne observatory to study X-rays from the stars.

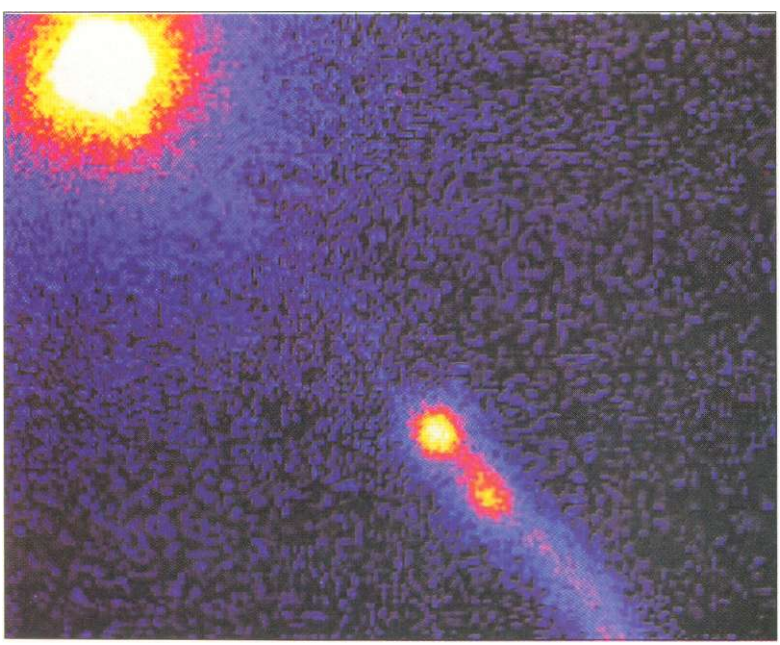

Plate XIV: The *Chandra X-ray Observatory* imaged a powerful jet shooting from the quasar 3C273.

Plate XV: The *Infrared Astronomical Satellite (IRAS)* was the first satellite exclusively devoted to infrared imaging of the sky.

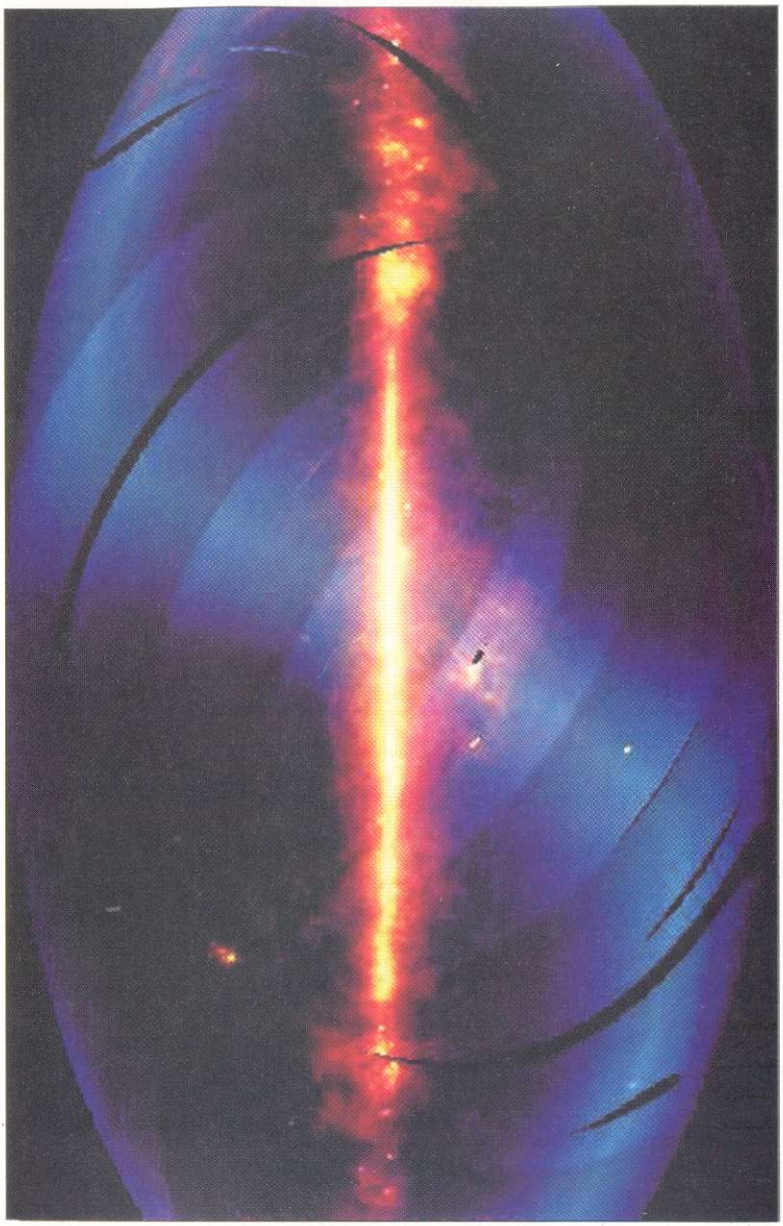

Plate XVI: Whole-sky images from *IRAS* show two bright intersecting bands, one associated with the plane of the Milky Way (the brighter band) and the other with the plane of Earth's orbit around the Sun (the S-shaped faint bluish band).

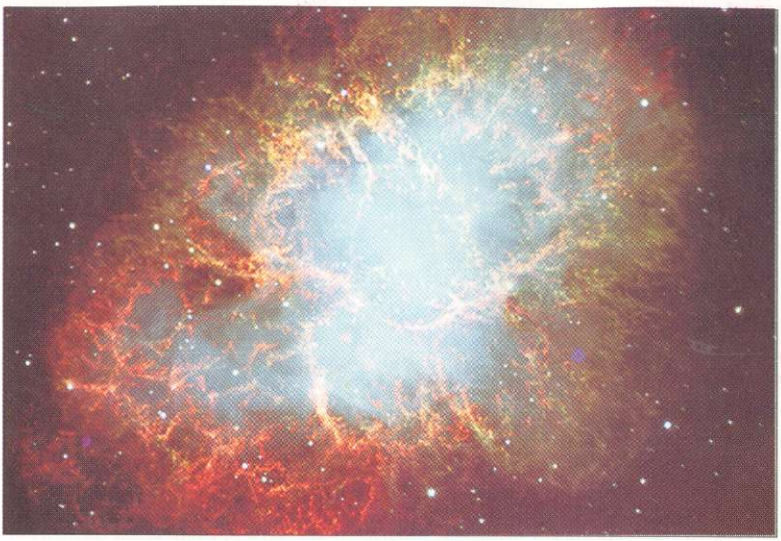

Plate XVII: The Crab Nebula as it appears through optical telescopes in visible light.

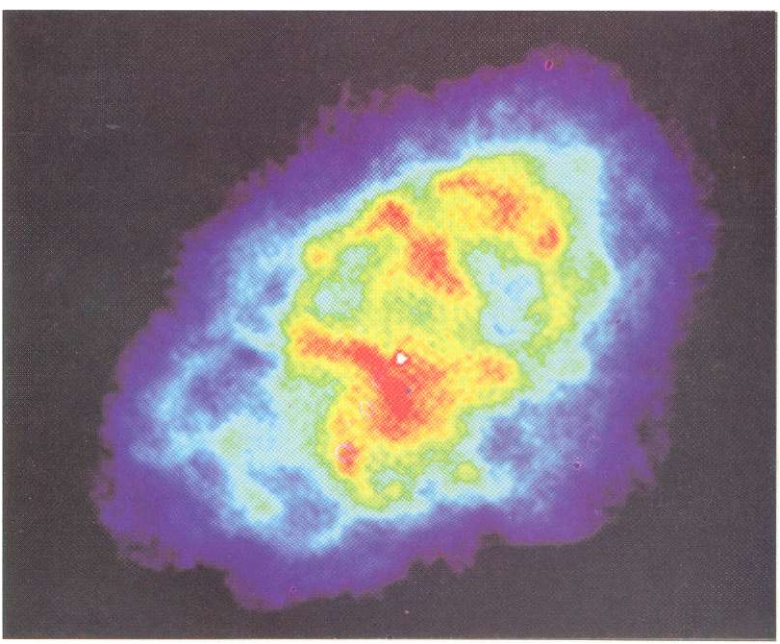

Plate XVIII: The Crab Nebula in radio wavelengths.

Plate XIX: X-ray view of the Crab Nebula.

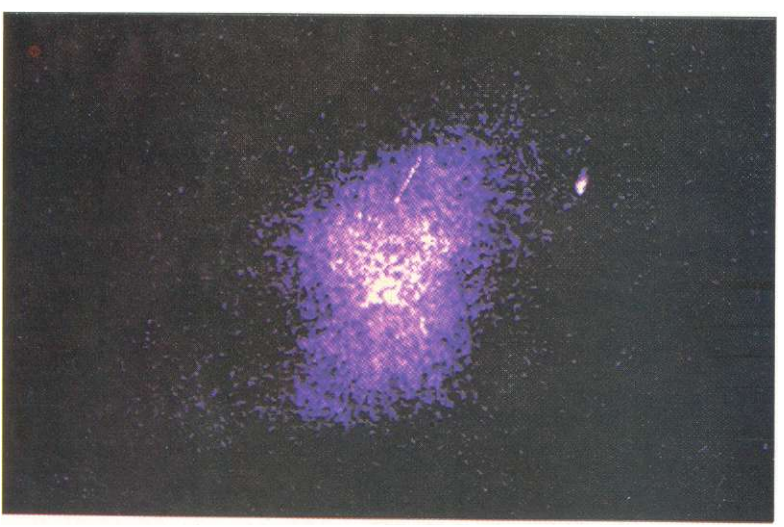

Plate XX: The Crab Nebula as it appears in the far ultraviolet wavelengths.

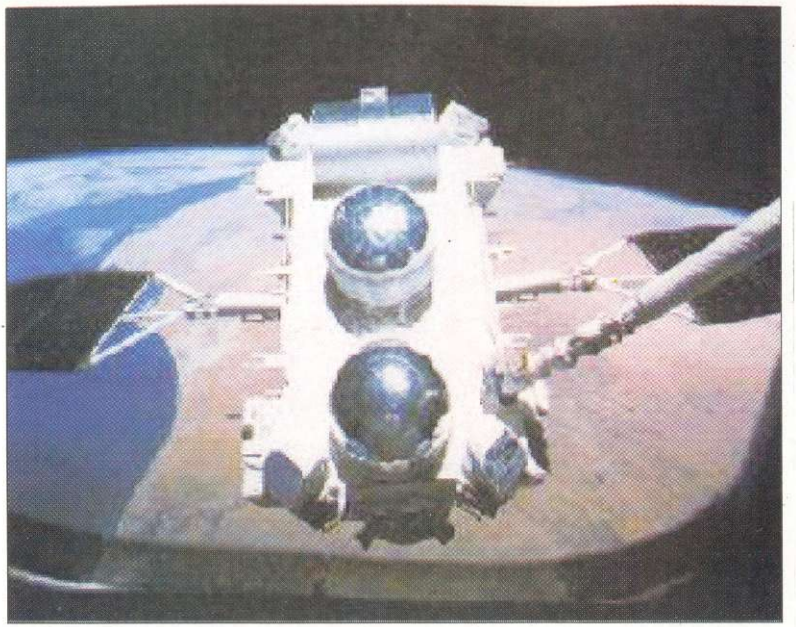

Plate XXI: The *Compton Gamma Ray Observatory (GRO)* was launched in April 1991 to probe gamma rays coming from space.

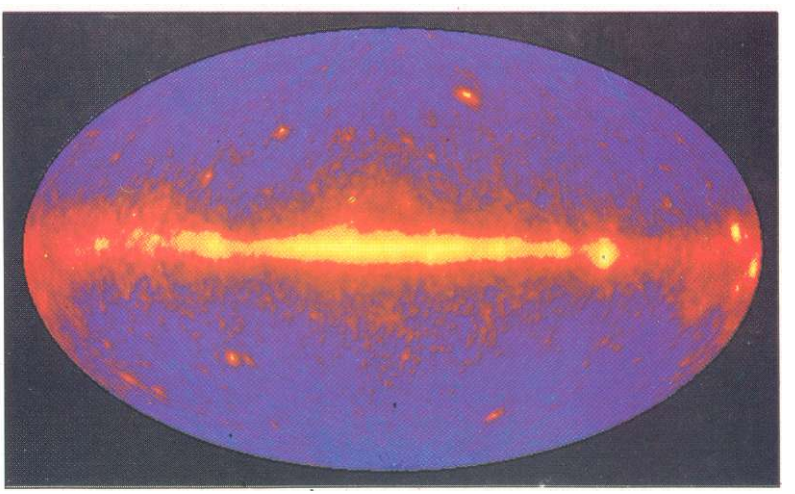

Plate XXII: Gamma ray sources in the sky are mainly located along the plane of our Milky Way galaxy, visible here as a yellow-orange band.

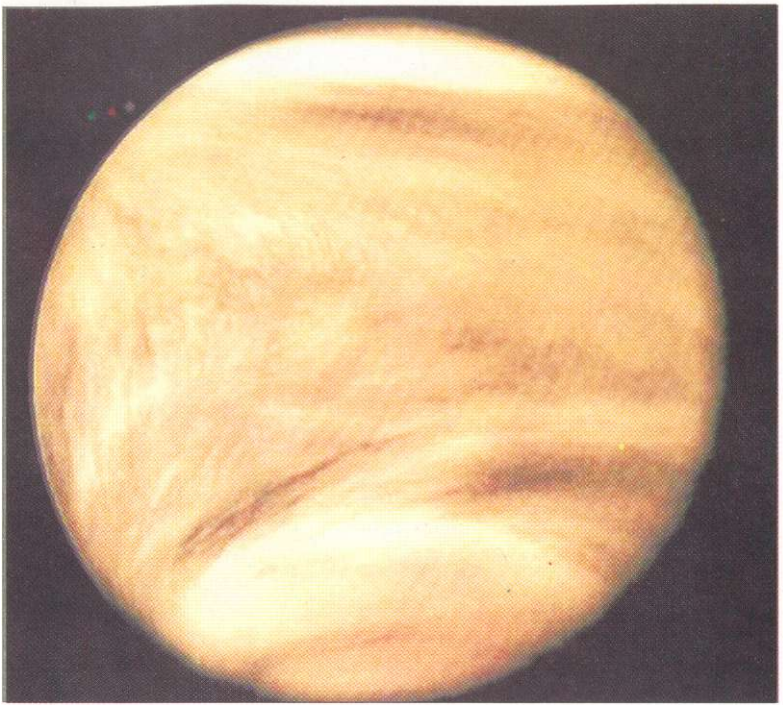

Plate XXIII: Through ground-based telescopes, Venus appears perpetually covered under a thick blanket of cloud.

Plate XXIV: False-colour image produced from radar signals sent back by the *Magellan* spacecraft show the surface of Venus to be covered with huge impact craters, volcanic craters and solidified lava flows.

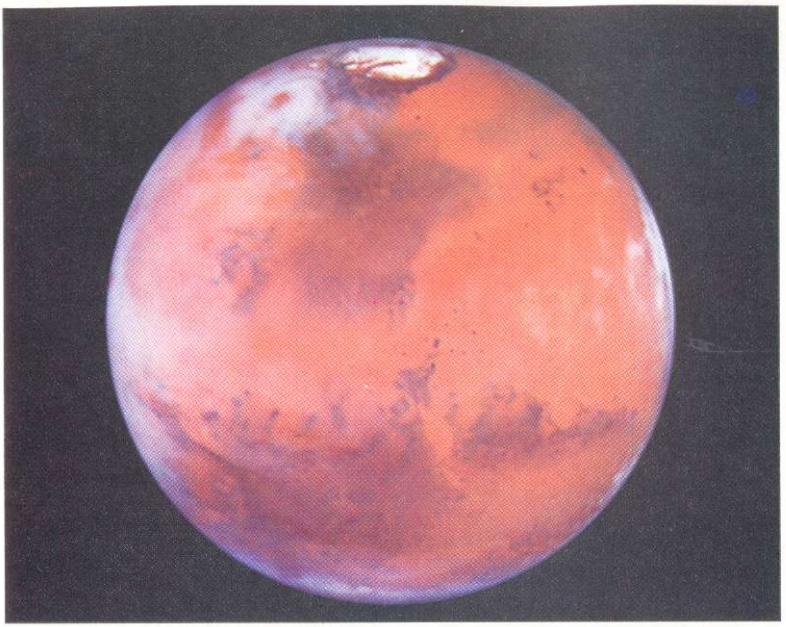

Plate XXV: Mars, as it appears through the Hubble Space Telescope.

Plate XXVI: The 25-km-high Olympus Mons on Mars is the largest volcano in the solar system.

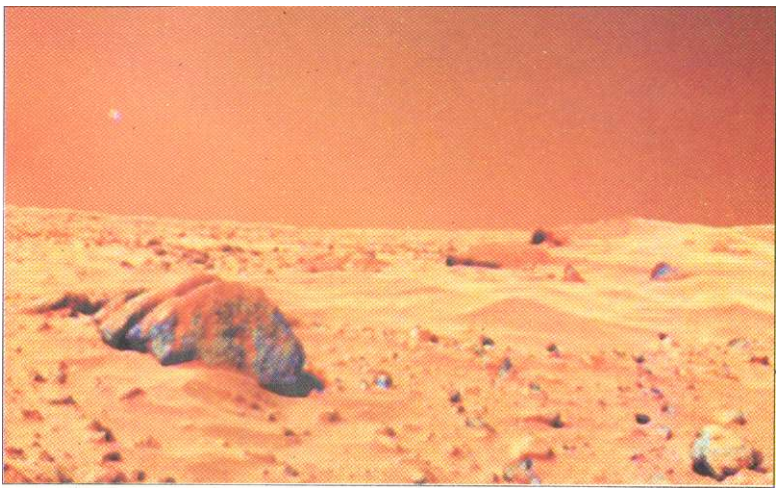

Plate XXVII: The orange-coloured surface of Mars, as seen by the *Viking* lander.

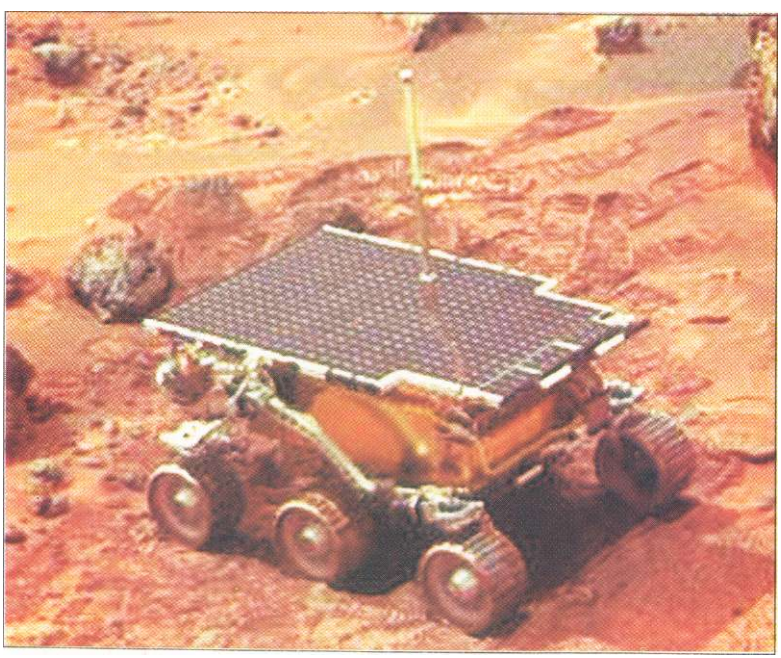

Plate XXVIII: The remote-controlled robot vehicle, *Sojourner,* which explored the Martian surface in 1997.

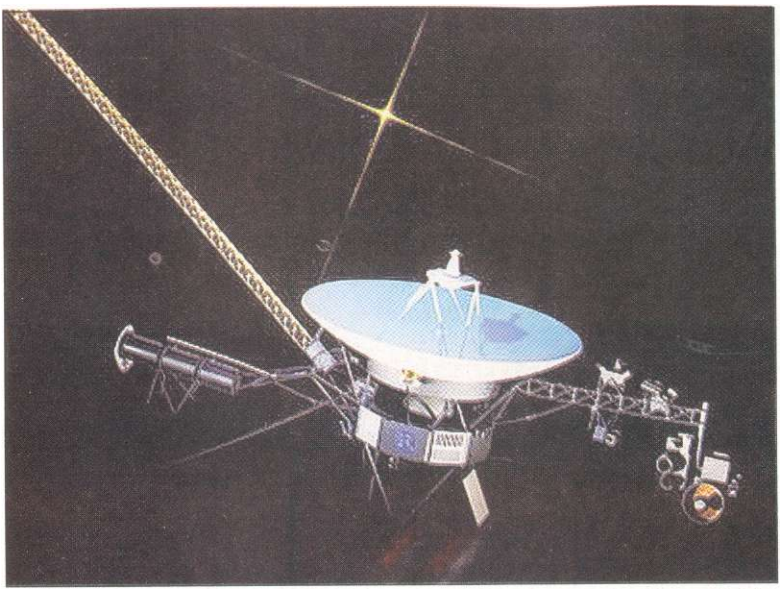

Plate XXIX: Two *Voyager* spacecraft explored the outer planets and sent back fantastic pictures and other data.

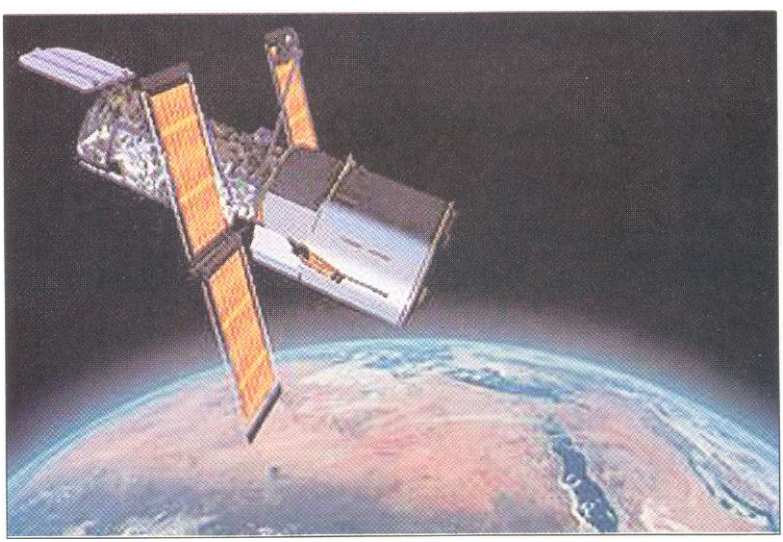

Plate XXX: The Hubble Space Telescope is the first orbiting observatory that has vastly expanded our reach to observe the universe in visible wavelengths.

Plate XXXI: The *Voyagers* sent back close-up pictures of Jupiter and its two moons.

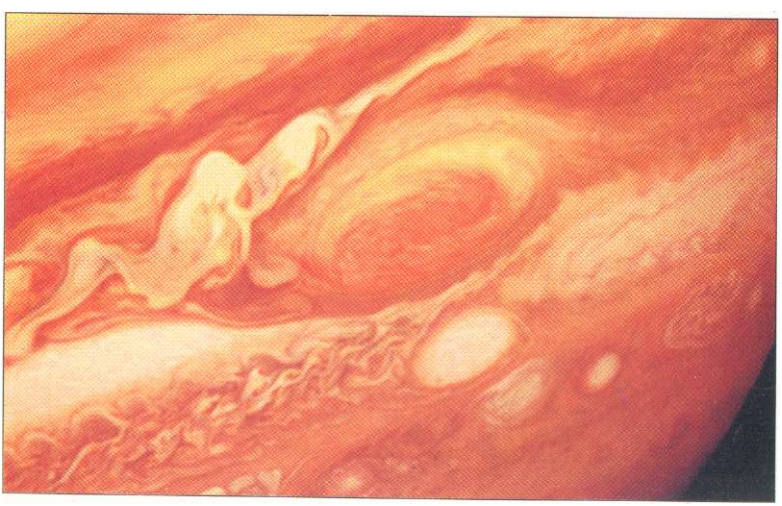

Plate XXXII: Jupiter's Great Red Spot, as seen by *Voyager.*

Plate XXXIII: The lava-filled surface of Io, which is the only body outside Earth with active volcanoes.

Plate XXXIV: The surface of Europa is covered with ice, with a 'cracked-eggshell' appearance.

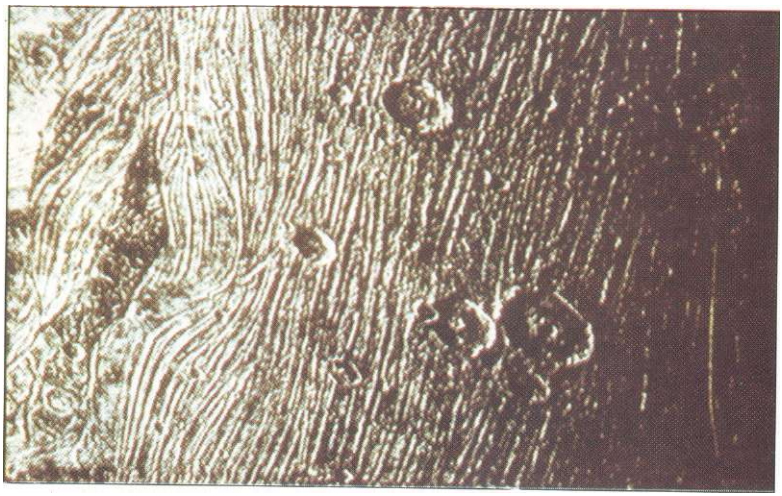

Plate XXXV: Ganymede is covered with dark cratered areas having lighter grooved terrain.

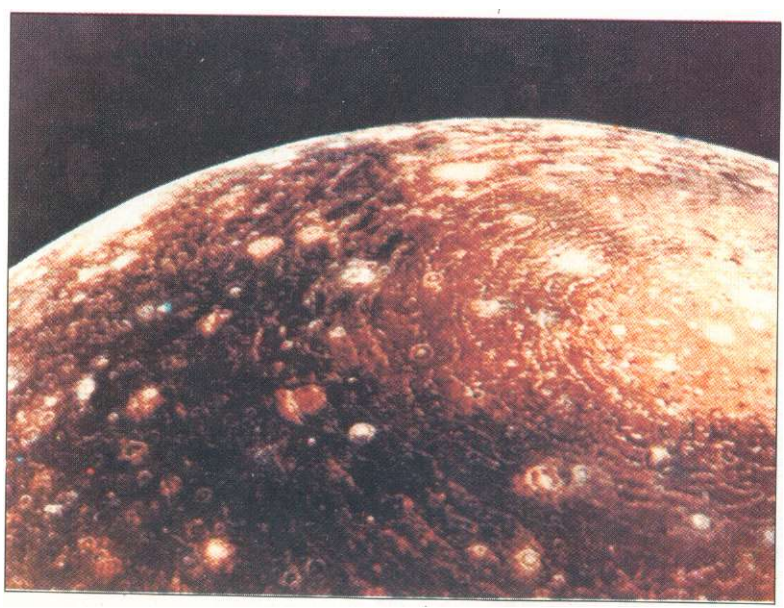

Plate XXXVI: The surface of Callisto is extensively cratered like Moon.

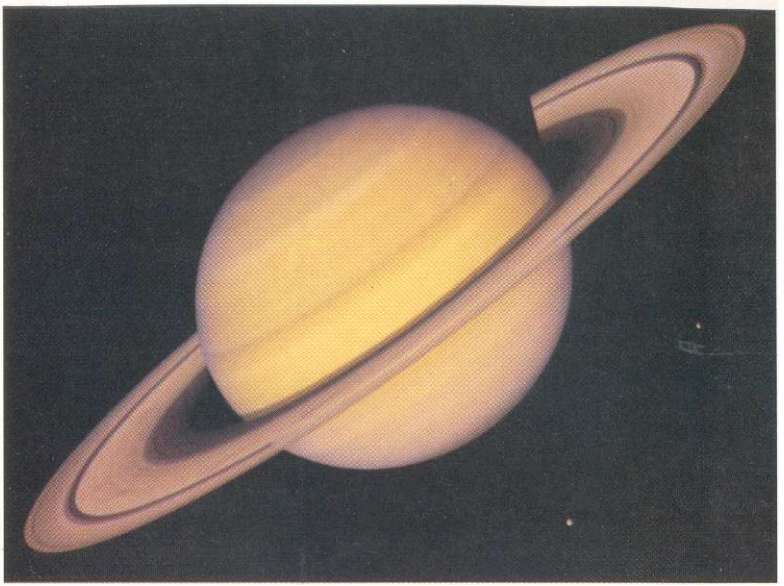

Plate XXXVII: Saturn, as seen from *Voyager*.

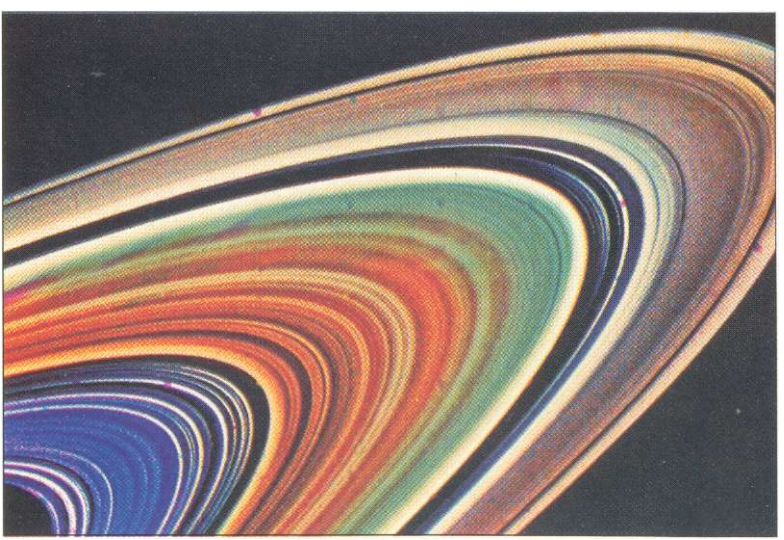

Plate XXXVIII: Images sent back by the *Voyagers* show that Saturn's rings are divided into thousands of narrow ringlets that give it the appearance of a grooved gramophone record, seen here in false colour.

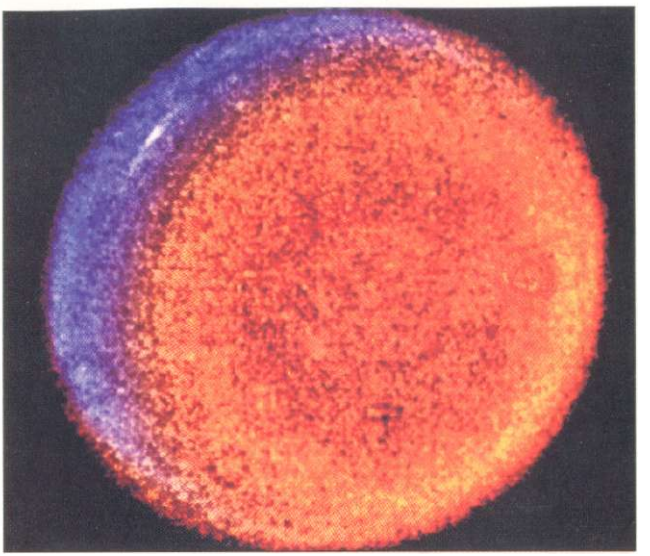

Plate XXXIX: Uranus turned out to be a planet literally rolling on its side with its south polar region facing the Sun at the time *Voyager 2* flew by in 1986. •

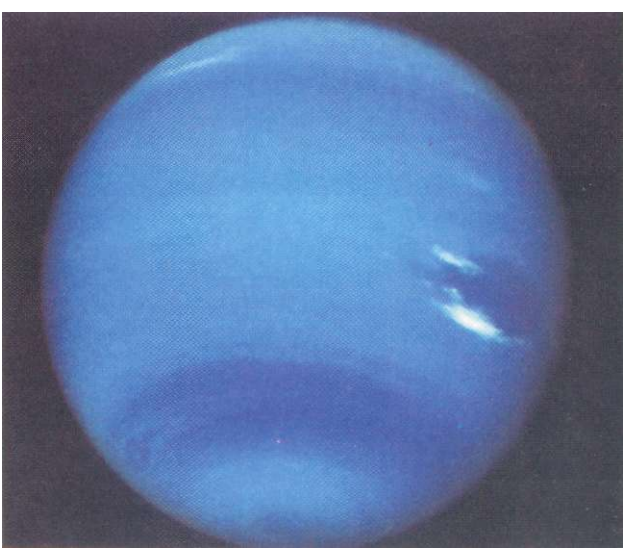

Plate XL: Voyager found Neptune to have a 'Great Black Spot' *(right),* almost resembling Jupiter's Great Red Spot.

Plate XLI: Image of a 'blank' piece of sky, taken by Hubble Space Telescope, shows hundreds of galaxies, some of which are about four billion times fainter than can be seen by the human eye. Some of these galaxies emitted their light when the universe was just one-third of its present age.

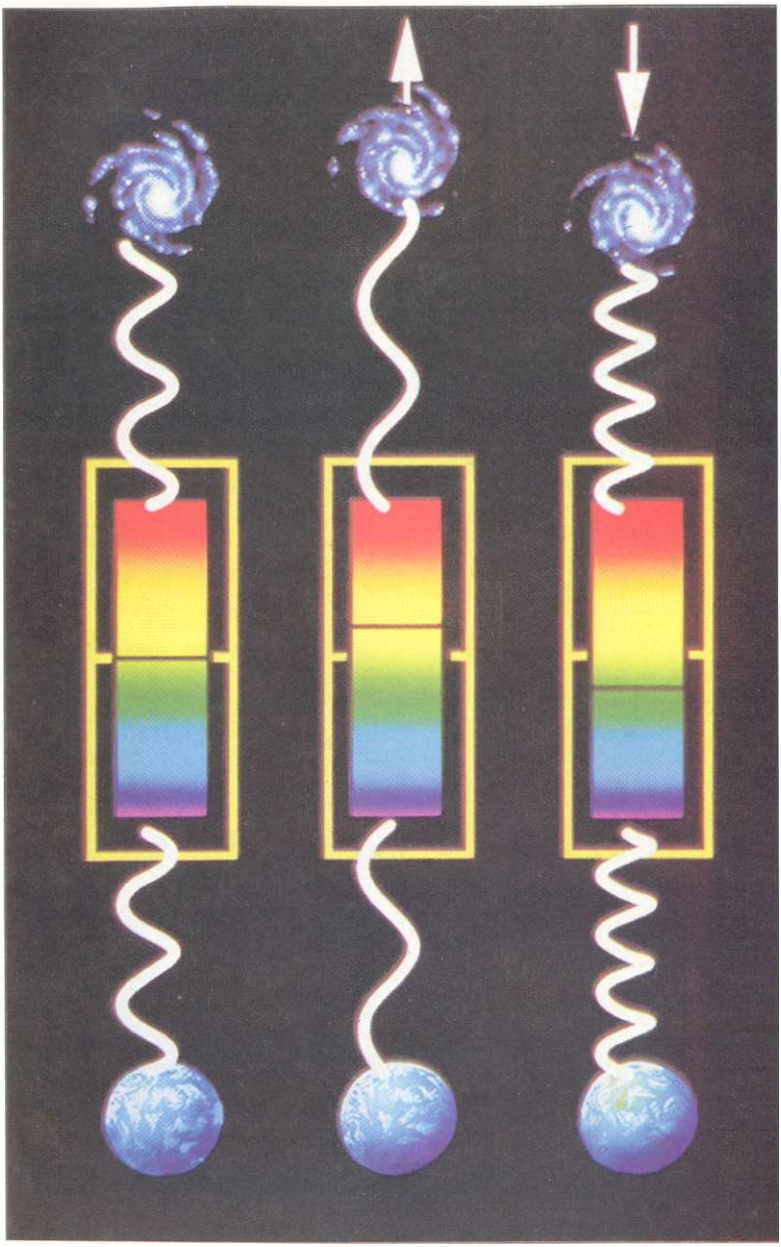

Plate XLII: Spectral lines shift towards the red end of the spectrum because light waves from the stars that are moving away from us appear to become stretched.

With advancements in observation techniques over the millennia, mankind's ideas about the cosmos have changed dramatically. Beginning with naked eye observation of the ancient astronomers, observation techniques have progressed dramatically with the invention of the optical telescope, radio telescope, and telescopes capable of "observing the cosmos in X-ray and gamma ray wavelengths. This book presents the exciting story of the unravelling of the cosmos, beginning with ancient ideas to the most recent findings made, using the latest technological tools.

Winner of the 1994 NCSTC National Award for best science and technology coverage in the mass media, Biman Basu has been engaged in science popularisation through print and electronic media for more than three-and-a-half decades. An M.Sc. in Chemistry from the University of Delhi, he taught Chemistry at Hans Raj College before joining the Council of Scientific & Industrial Research. He edited the popular science monthly, *Science Reporter* and has written more than 10 popular science books, of which three, *The Story of Man* (1997), *Joy of Starwatching* (1999), and *Marching Ahead with Science* (2001) have been published by NBT.

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